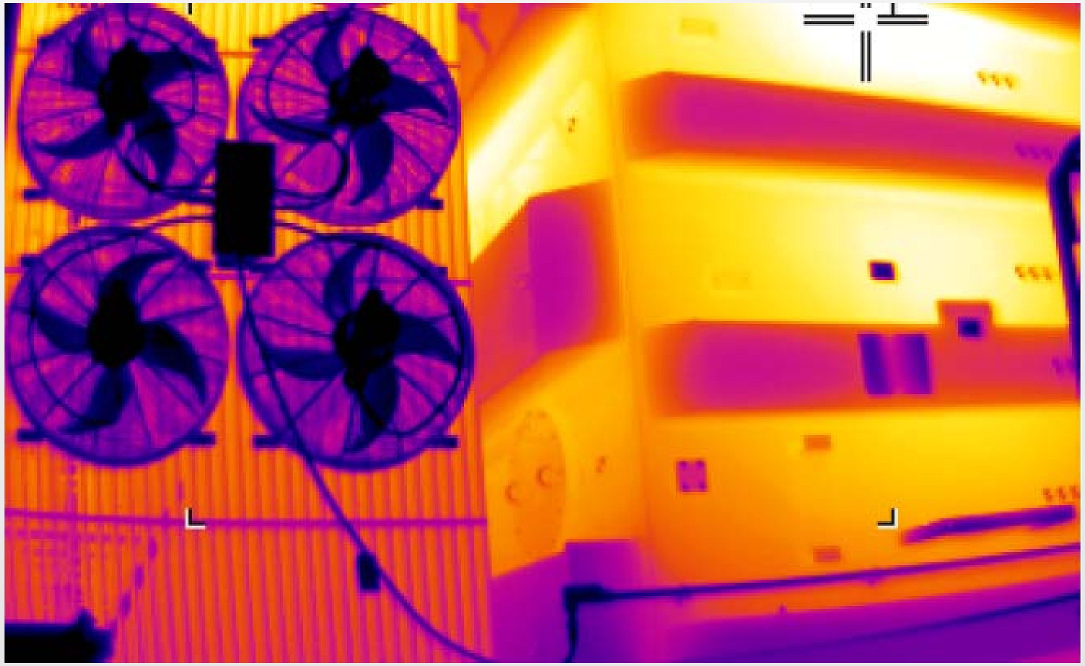
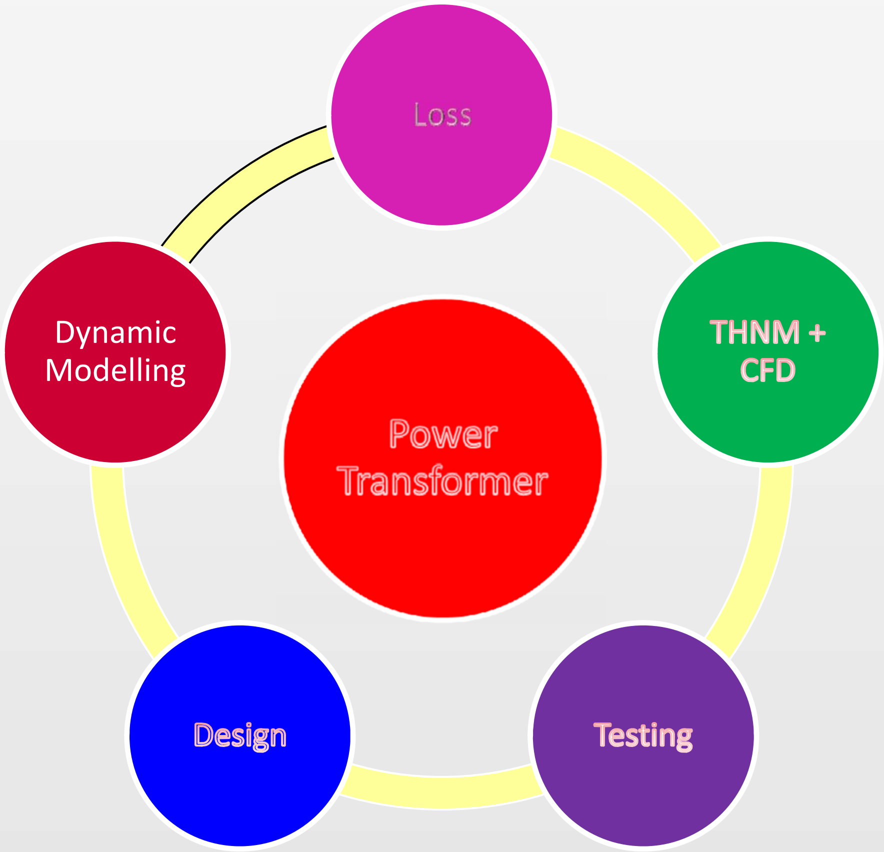
Dynamic Thermal Modelling of Power Transformer

IEC 60076-7 Methodology



Dejan Susa
(dejan.susa@statnett.no)

Power Transformer Thermal Modelling

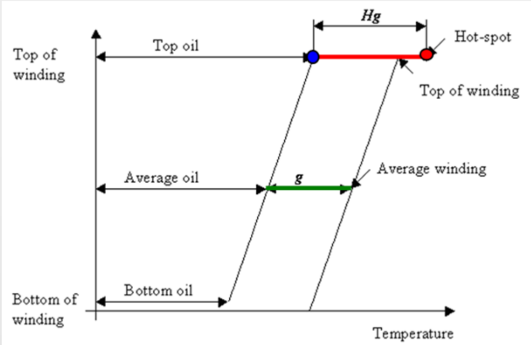


Loading Guide for Oil-Immersed Power Transformers IEC 60076-7

- IEC 60076-7 loading guide for oil immersed power transformers indicates how oil-immersed transformers can be operated in different ambient conditions and load levels without exceeding the acceptable deterioration limit of insulation due to thermal effects.

- hot-spot temperature in a transformer winding consists of three components:
  - ambient temperature
  - top-oil temperature rise
  - hot-spot to top-oil gradient

$$\theta_h(t) = \theta_a(t) + \Delta\theta_o(t) + \Delta\theta_{h-o}(t)$$



- both temperature rises during a transient period, i.e. in changing from one steady state to another, could be modelled by functions of the exponential form

Dynamic Thermal Modelling of Power Transformers: Why?

- Hot-Spot Temperature
  - Loading Capacity
  - Protection
  - Ageing
  - Cooling Control
  - Run different loading and ambient scenarios

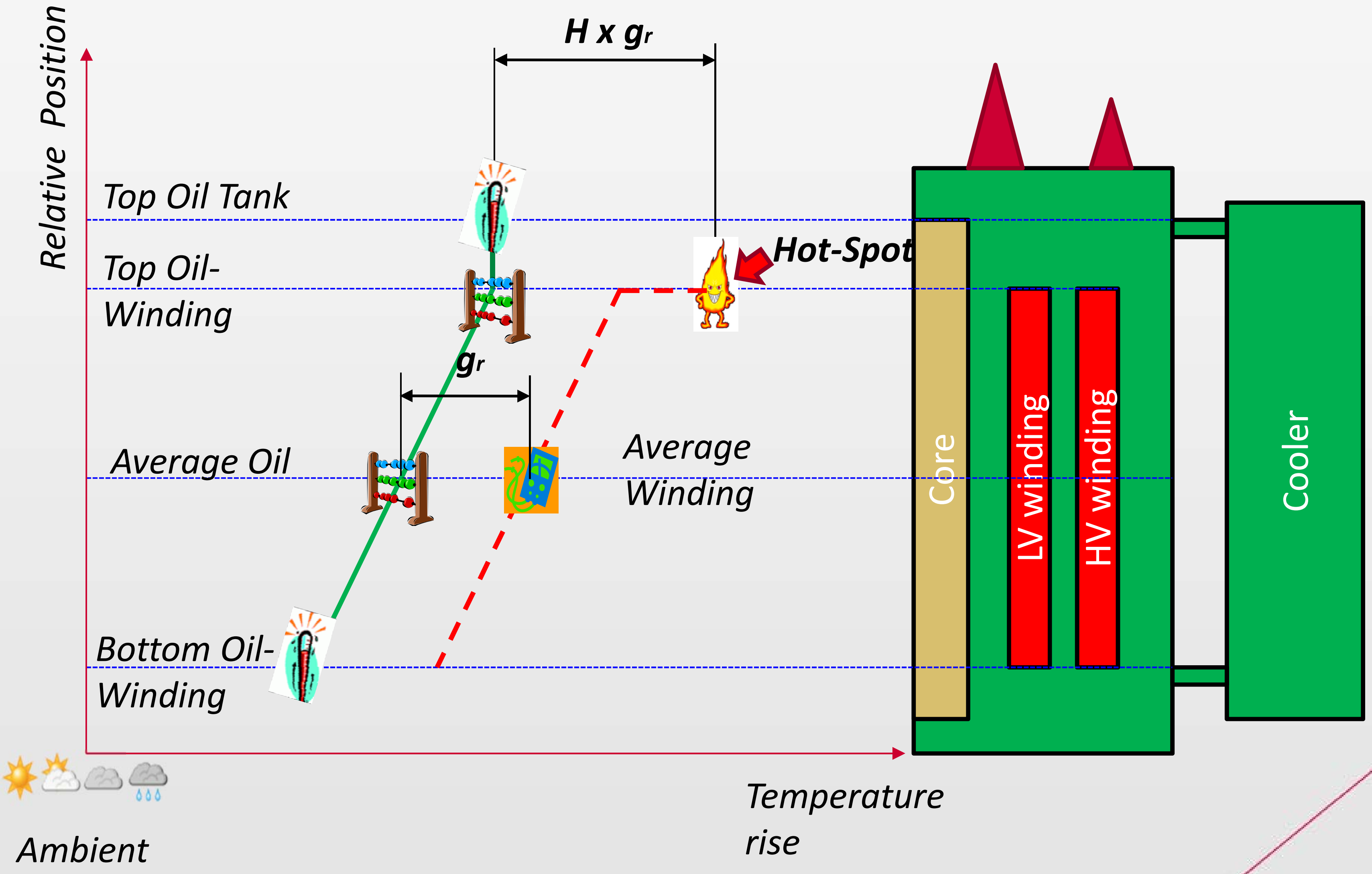
$$\theta_{\mathrm{h}}(t) = \theta_{\mathrm{a}} + \Delta\theta_{\mathrm{oi}} + \left\{ \Delta\theta_{\mathrm{or}} \times \left[\overbrace{\frac{1 + R \times K^2}{1 + R}}^{\text{Loss equation}} \right]^x - \Delta\theta_{\mathrm{oi}} \right\} \times f_1(t) + \Delta\theta_{\mathrm{hi}} + \left\{ H g_{\mathrm{r}} K^y - \Delta\theta_{\mathrm{hi}} \right\} \times f_2(t)$$

Ambient temperature

Oil temperature rise

Hot-spot to top-oil gradient

Dynamic Thermal Model Characteristic Temperatures: Simplified



Statnett

HEAT RUN TEST

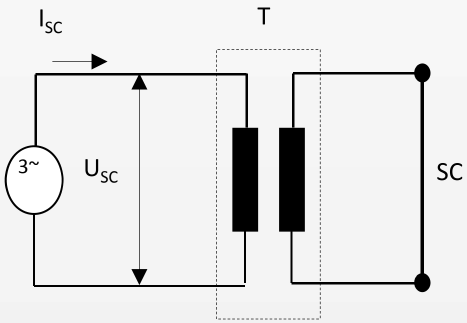
- **The heat run test, i.e. temperature rise test, is the type test carried out to verify the guaranteed temperature rises for oil and windings**

- **It is also used to reveal the possible overheated locations inside and outside windings due to high stray fields for the high powers**

- **In addition, as indicated above, the temperature rises obtained during a heat-run test are used for estimating transformer loading capability by application of the relevant thermal models**

- During a heat run test the following temperatures could be directly measured:
  - Ambient temperature
  - Top-oil temperature
  - Bottom-oil temperature
  - Hot-spot temperature, hottest winding temperature (if fiber optic sensors are installed)

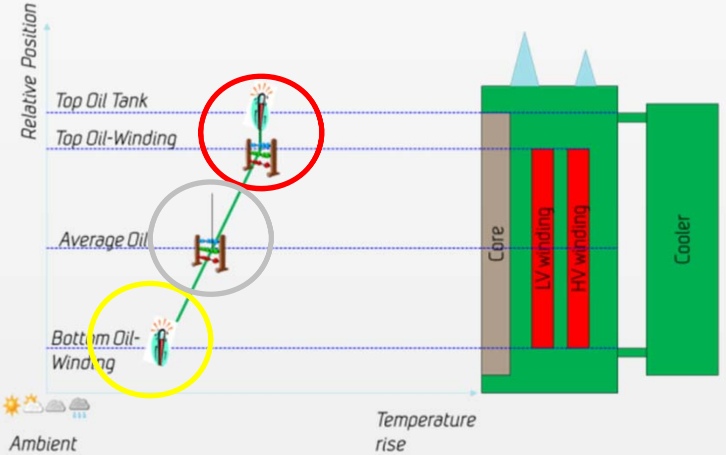
- There are two methods used for performing the heat run test:
  - short circuit
  - back-to-back

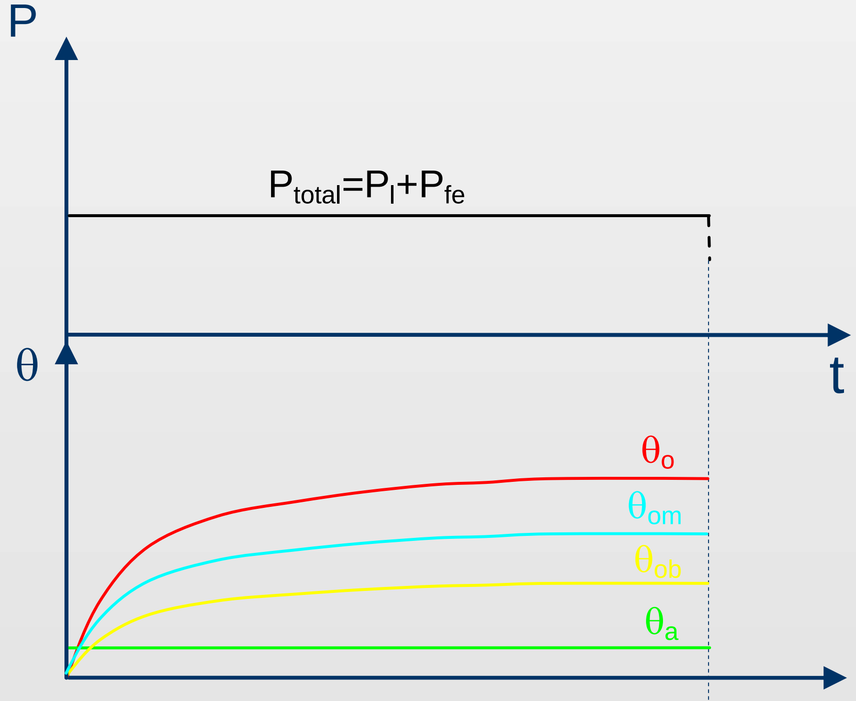


$I_{SC}=k\cdot I_r$ and

$U_{SC}=k\cdot U_{SC(Ir)}$

$$\boxed{k=\sqrt{\frac{P_l+P_{fe}}{P_l}}}$$





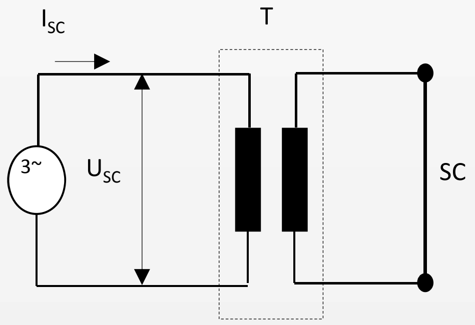
Step 1

$$\boxed{\Delta\theta_o=\theta_o-\theta_a}$$

$$\boxed{\Delta\theta_{ob}=\theta_{ob}-\theta_a}$$

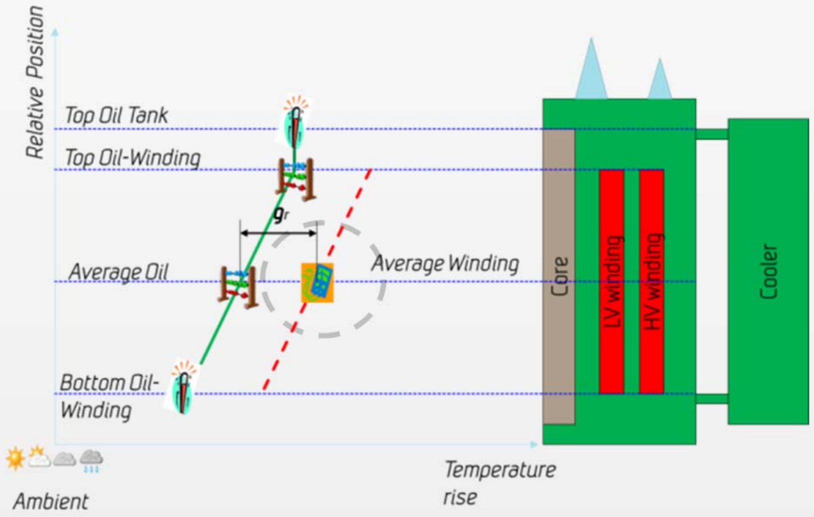
$$\boxed{\theta_{om}=\frac{\theta_o+\theta_{ob}}{2}}$$

$$\boxed{\Delta\theta_{om}=\theta_{om}-\theta_a}$$

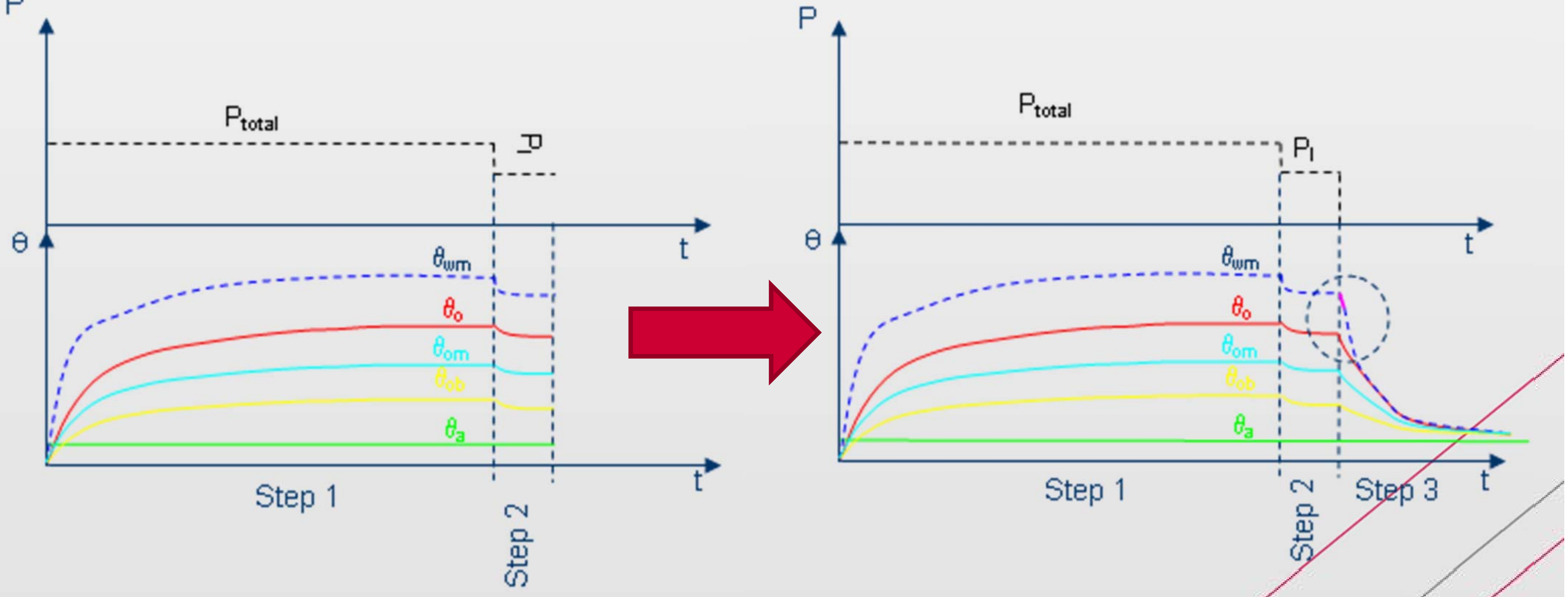


I_{SC}
T
3~
U_{SC}
SC

$I_{SC}=I_r$



Relative Position
Top Oil Tank
Top Oil-Winding
g_r
Average Oil
Average Winding
Bottom Oil-Winding
Ambient
Temperature rise
Core
LV winding
HV winding
Cooler



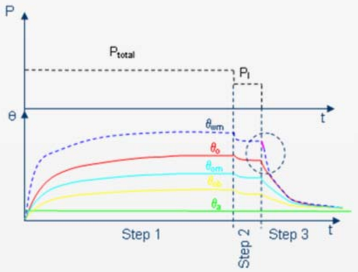
P
P_{total}
P_l
θ
t
θ_{wm}
θ_o
θ_{om}
θ_{ob}
θ_a
t
Step 1
Step 2
P
P_{total}
P_l
θ
t
θ_{wm}
θ_o
θ_{om}
θ_{ob}
θ_a
t
Step 1
Step 2
Step 3

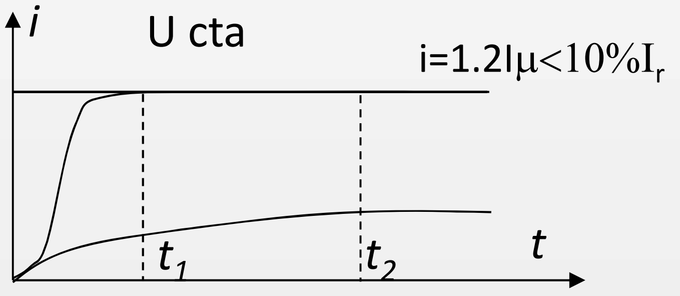
Cooling Curve Warm Resistance

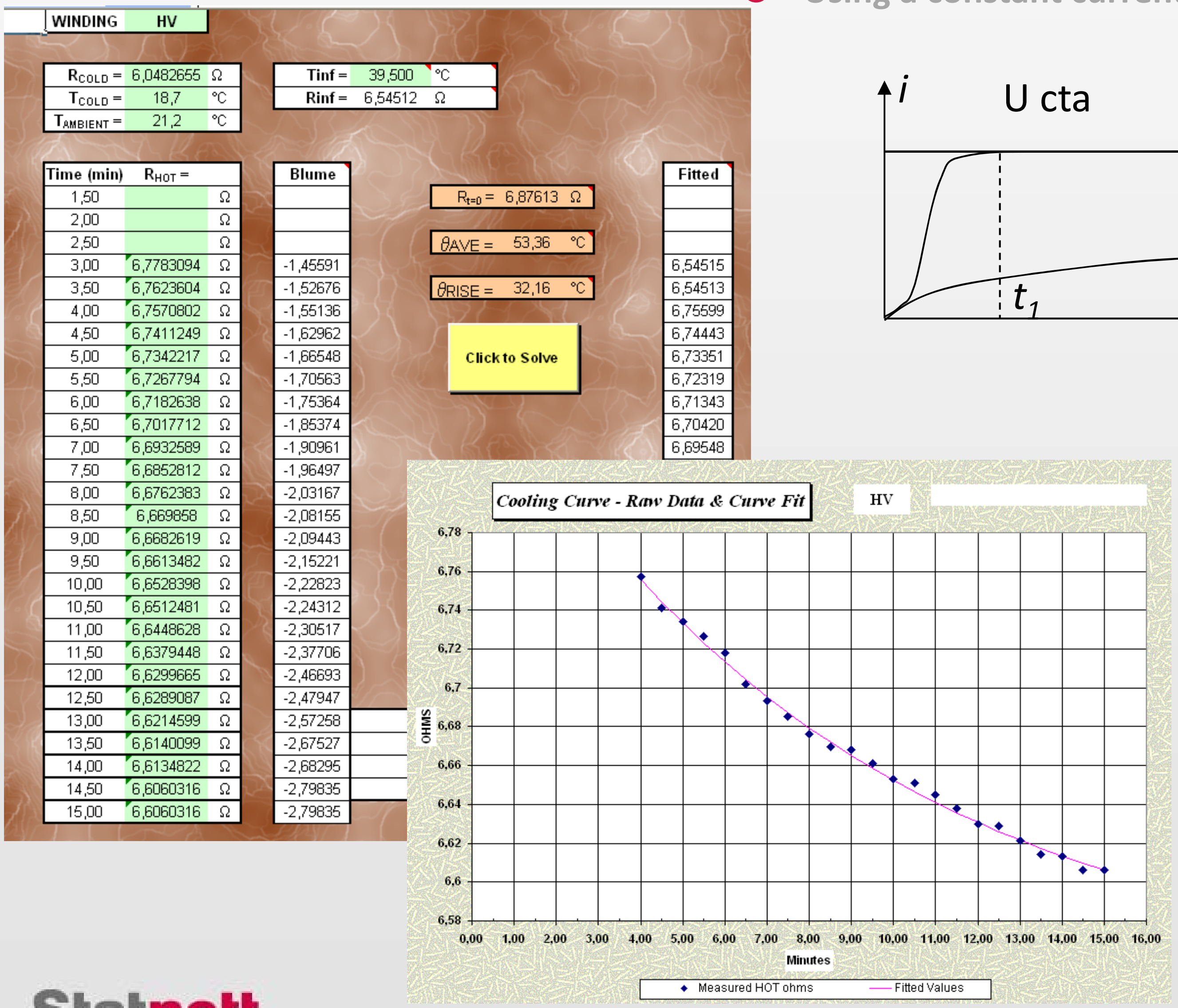
- Inductive voltage drop in the winding:

  $U = Ri + C\,d\Phi/dt = Ri + L\,di/dt$

  - d.c. measuring current must be stabilized
    - Using a constant current-supply







WINDING	HV

R_{COLD} =	6,0482655	Ω
T_{COLD} =	18,7	°C
$T_{AMBIENT}$ =	21,2	°C

Tinf =	39,500	°C
Rinf =	6,54512	Ω

$R_{t=0}$ = 6,87613 Ω

θAVE = 53,36 °C

θRISE = 32,16 °C

Click to Solve

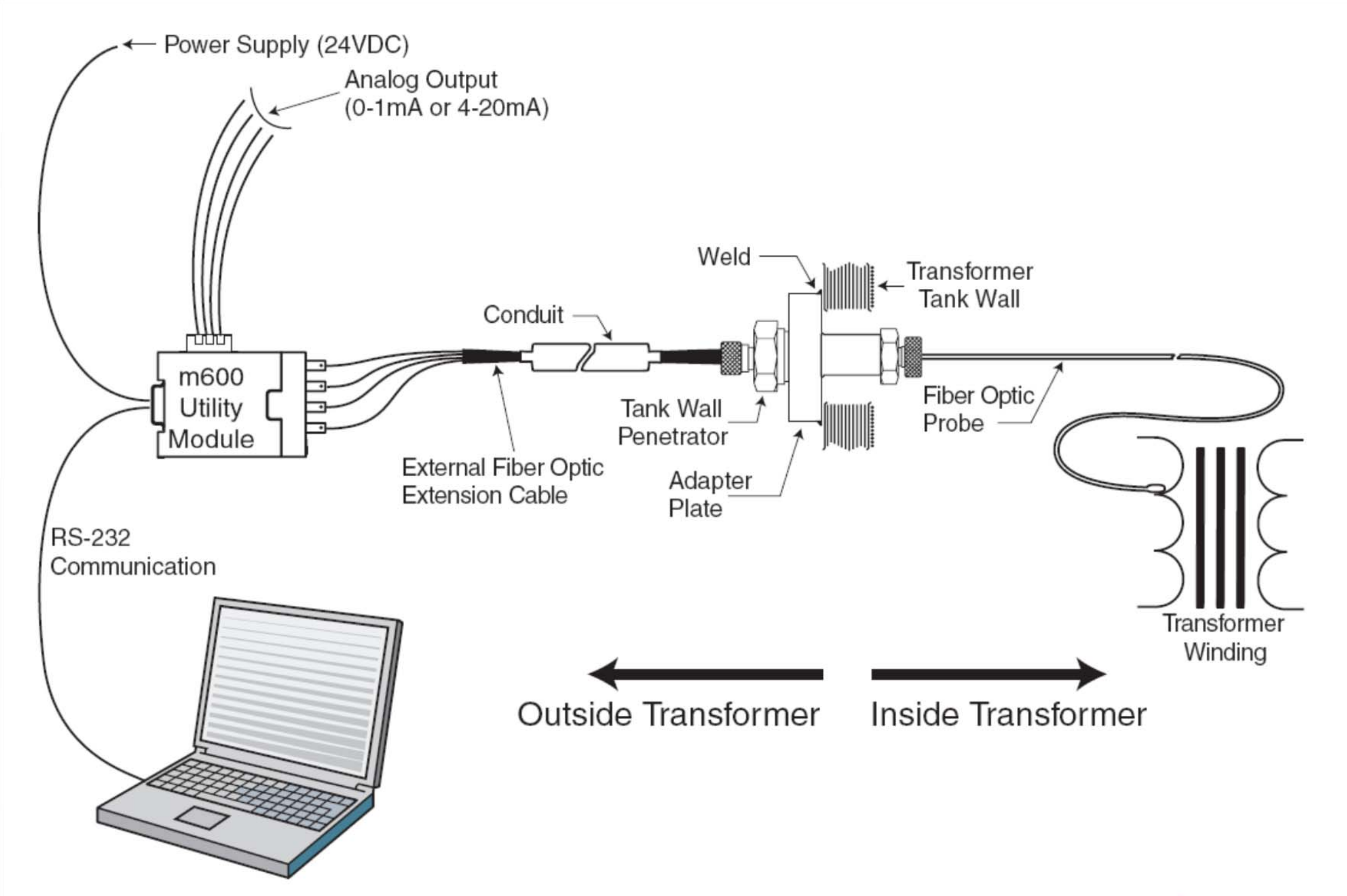
Time (min)	R_{HOT} =		Blume	Fitted
1,50		Ω		
2,00		Ω		
2,50		Ω		
3,00	6,7783094	Ω	-1,45591	6,54515
3,50	6,7623604	Ω	-1,52676	6,54513
4,00	6,7570802	Ω	-1,55136	6,75599
4,50	6,7411249	Ω	-1,62962	6,74443
5,00	6,7342217	Ω	-1,66548	6,73351
5,50	6,7267794	Ω	-1,70563	6,72319
6,00	6,7182638	Ω	-1,75364	6,71343
6,50	6,7017712	Ω	-1,85374	6,70420
7,00	6,6932589	Ω	-1,90961	6,69548
7,50	6,6852812	Ω	-1,96497	
8,00	6,6762383	Ω	-2,03167	
8,50	6,669858	Ω	-2,08155	
9,00	6,6682619	Ω	-2,09443	
9,50	6,6613482	Ω	-2,15221	
10,00	6,6528398	Ω	-2,22823	
10,50	6,6512481	Ω	-2,24312	
11,00	6,6448628	Ω	-2,30517	
11,50	6,6379448	Ω	-2,37706	
12,00	6,6299665	Ω	-2,46693	
12,50	6,6289087	Ω	-2,47947	
13,00	6,6214599	Ω	-2,57258	
13,50	6,6140099	Ω	-2,67527	
14,00	6,6134822	Ω	-2,68295	
14,50	6,6060316	Ω	-2,79835	
15,00	6,6060316	Ω	-2,79835	

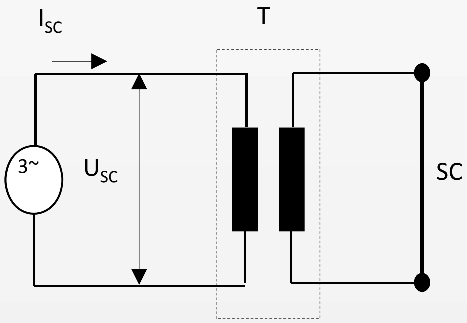
$$\theta'_{wm} = \frac{R_w}{R_a} \times (\alpha + \theta_a) - \alpha$$

$$g = \theta'_{wm} - \theta_{om(I_r)}$$

$$\theta_{om(I_r)} = \frac{\theta_{o(I_r)} + \theta_{ob(I_r)}}{2}$$

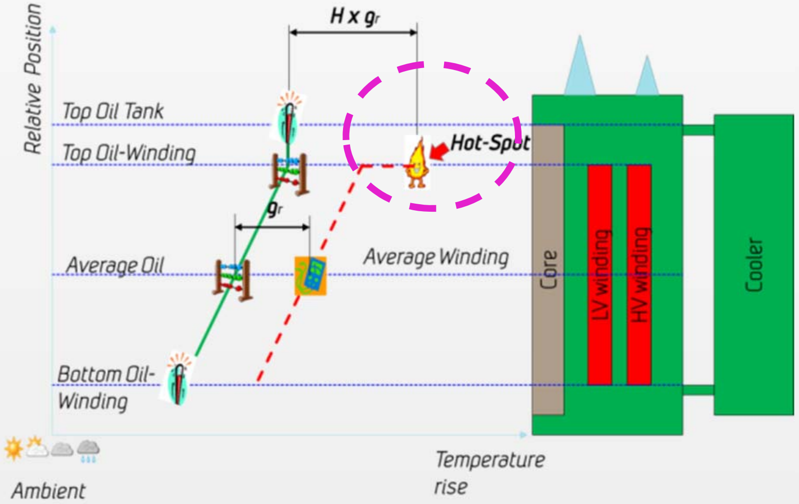
Hot-Spot Temperature Direct Measurements

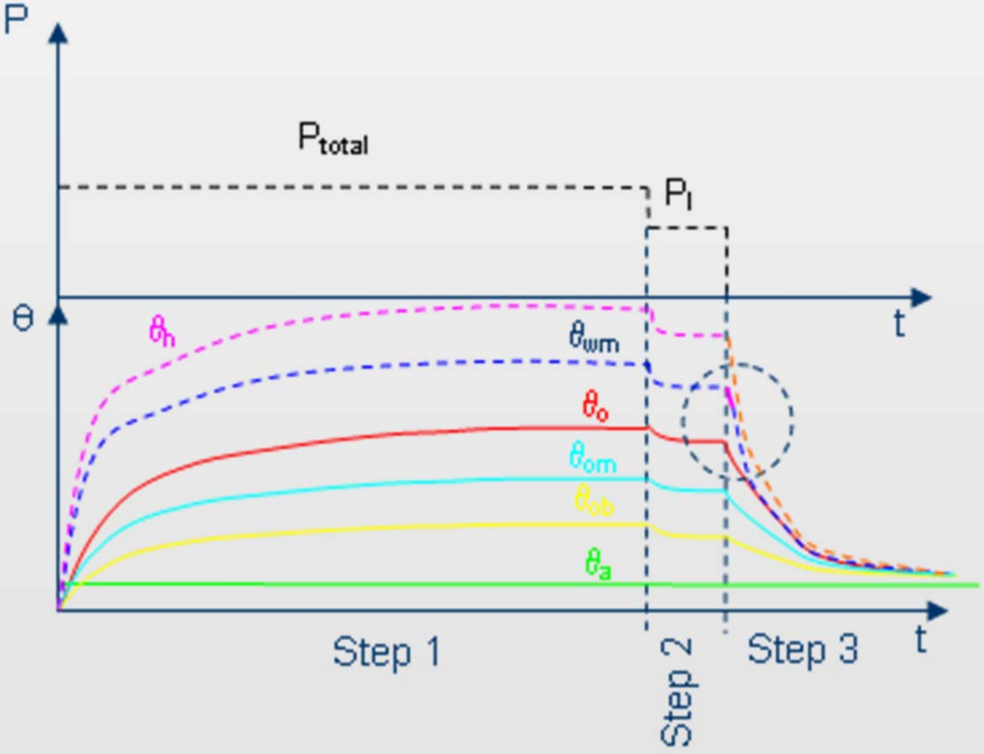




Step 1: $I_{SC}=kI_r$

Step 2: $I_{SC}=I_r$





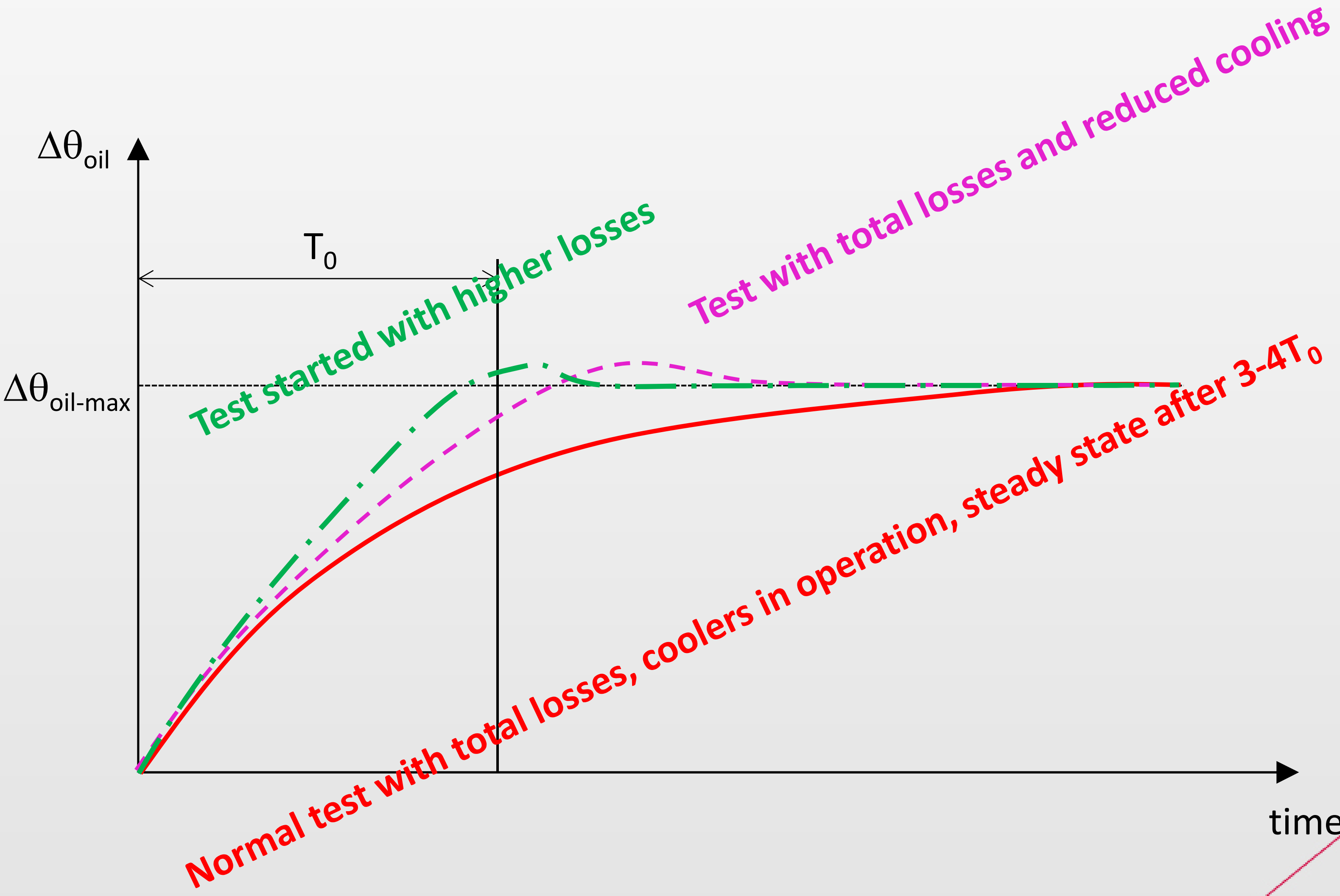
$$\Delta\theta_{h-o} = \theta_h - \theta_{o(I_r)}$$

$$\Delta\theta_{h-o} = H \times g$$

$$H = \frac{\Delta\theta_{h-o}}{g}$$

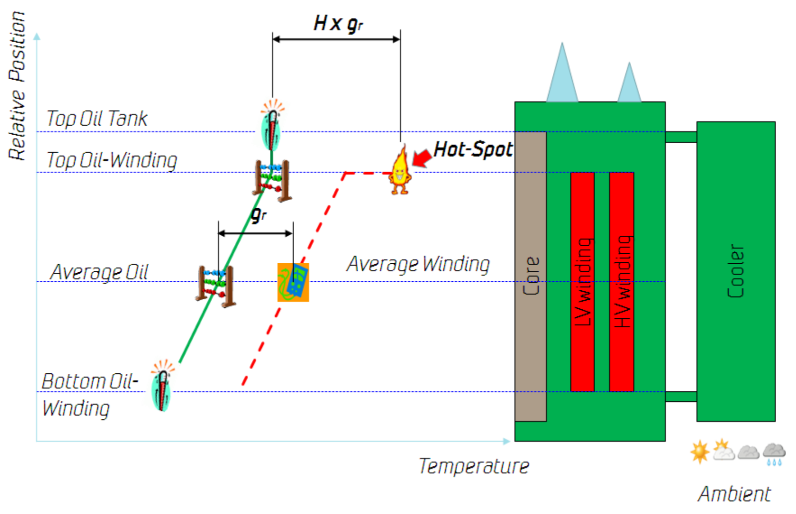
$$\Delta\theta_h = \Delta\theta_o + \Delta\theta_{h-o}$$

Specification

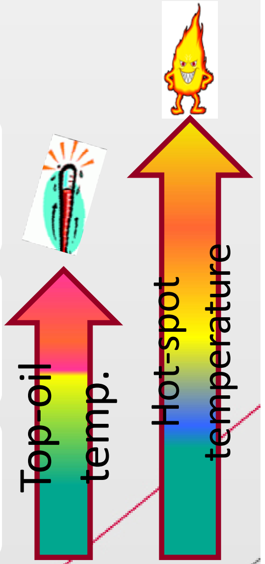


Statnett

Steady state: Top-oil and Hot-spot Temperatures



Hot-spot to top-oil gradient	$= H \cdot g_r \cdot K^y$
Top-oil rise over ambient	$=(\text{Top-oil rise})_r \cdot [(1+R\text{x}K^2)/(1+R)]^x$
Ambient Temperature	Ambient Temperature



Steady State Equations Background

Presented at the 33rd Annual Convection of the American Institute of Electrical Engineers, Cleveland , O., June 27, 1916: **Effect of Barometric Pressure on Temperature Rise of Self-Cooled Stationary Induction Aparatus by V.M: Montsinger**

1. **Dulong and Petit Law, 1817: "The velocity of the cooling due solely to the contact of a gas is proportional to the excess of temperature in degrees centigrade raised to the power 1.233", This was later verified by Peclet!**
2. **Lorenz (Ann. D. Physik, Vol. 13, p 582), 1881 derived for convection of heat from vertical plane surface:**

$$W_c=\underline{0.548\bullet[(c \bullet g \bullet K^3)/(h \bullet H \bullet \theta_1)]^{1/4}} \bullet \rho^{0.5} \,\underline{\bullet}\, \Delta\underline{\theta^{1.25}} = \underline{C^{te}} \,\underline{\bullet}\, \Delta\underline{\theta^{1.25}}$$

Where: Wc is heat convection per sq. Cm. Of surface, c is specific heat of gas at constant pressure, K is gas thermal conductivity, h is gas viscosity, θ_1 is gas average temperature, ρ is gas average density, g is gravitional content, H is height of plane and Δθ is difference in temperature of plane surface and of the gas at a great distance forme the plane.

3. **Montsinger**

- ❑ Top-oil temperature rise:

$$P=C^{te} \bullet \underline{\Delta\theta^{1.25}} \Longrightarrow \Delta\theta=k \bullet P^{0.8}$$

$$\Delta\theta/\Delta\theta_r=(k/k_r) \bullet (P/P_r)^{0.8} \Longrightarrow k=k_r \Longrightarrow \Delta\theta=(P/P_r)^{0.8} \times \Delta\theta_r \Longrightarrow R= P_{lr}/P_{fer}\,;\ P=P_l+P_{fe};\ P_r=P_{lr}+P_{fer}\,;P_{fer}=P_{fe}$$

$$\Delta\theta=[(1+R \bullet K^2)/(1 \bullet R)]^{0.8} \bullet \Delta\theta_r\,;\ K^2=P_l/P_{lr}\,,\ x=0.8\text{-IEC 60076-7}$$

$$\text{Top-oil rise}= (\text{Top-oil rise})_r \bullet[(1+R \bullet K^2)/(1+R)]^x$$

Steady State Equations Background

- ❑ Hot-spot temperature rise over top-oil temperature:
  - ➢ Disc winding

$$P=C^{te} \bullet \underline{\Delta\theta^{1.25}} \Longrightarrow \Delta\theta=k \bullet P^{0.8}$$

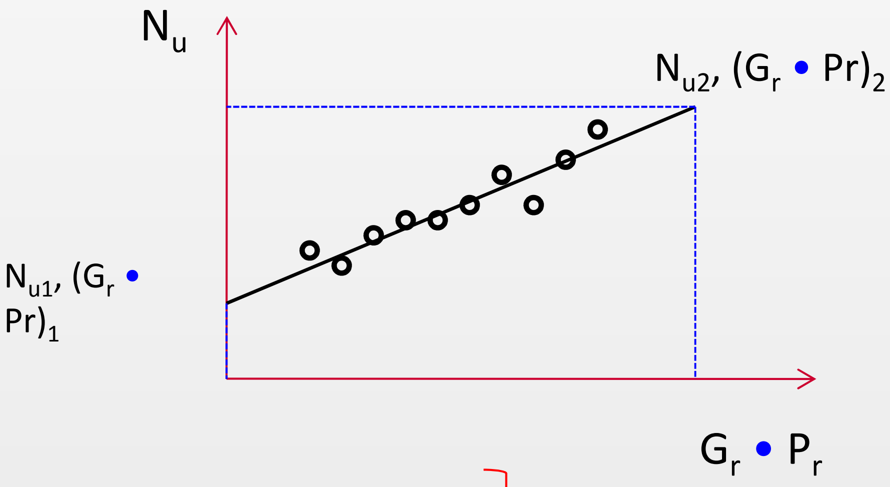
$$\Delta\theta_d/\Delta\theta_{dr} =(k_d/k_{dr}) \bullet (P_l/P_{lr})^{0.8} \Longrightarrow k_d=k_{dr} \Longrightarrow \Delta\theta_d =\Delta\theta_{dr} \bullet (K^2)^{0.8} \Longrightarrow \Delta\theta_{dr} = H \bullet g_r$$

$\Delta\theta_d = H \bullet g_r \bullet K^{1.6}$, y=1.6 (IEC 354, IEC 60076-2), y=1.3 (IEC 60076-7)

Hot-spot to top-oil gradient= $H \bullet g_r \bullet K^y$

Steady State Equations Background

- ☐ Natural convection around vertical, inclined and horizontal plates and cylinders
  - ➢ $N_u=C\bullet[G_r\bullet P_r]^n$
  - ➢ Nusselt-$N_u=(\alpha\bullet h)/\lambda$
  - ➢ Prandtl- $P_r=(\rho\bullet\nu\bullet c)/\lambda$
  - ➢ Grashof- $G_r=(\beta\bullet\Delta\theta\bullet g\bullet h^3)/\nu^2$
- ☐ Measured:
  - ✓ Oil Temperature
  - ✓ Hot-spot temperature
  - ✓ Surface heat flux, P
- ☐ Calculated:
  - ➢ Surface temp. drop, $\Delta\theta$
  - ➢ Mean boundary layer temp, θ_m
  - ➢ Average heat transfer coefficient, $\alpha=P/\Delta\theta$



$$\left.\begin{aligned}N_{u1}&=C\bullet[(G_r\bullet P_r)_1]^n\\N_{u2}&=C\bullet[(G_r\bullet P_r)_2]^n\end{aligned}\right\}\ n,\ C$$

$$N_u=C\bullet[G_r\bullet P_r]^n\Longrightarrow\alpha=C^{te}\bullet\Delta\theta^n$$

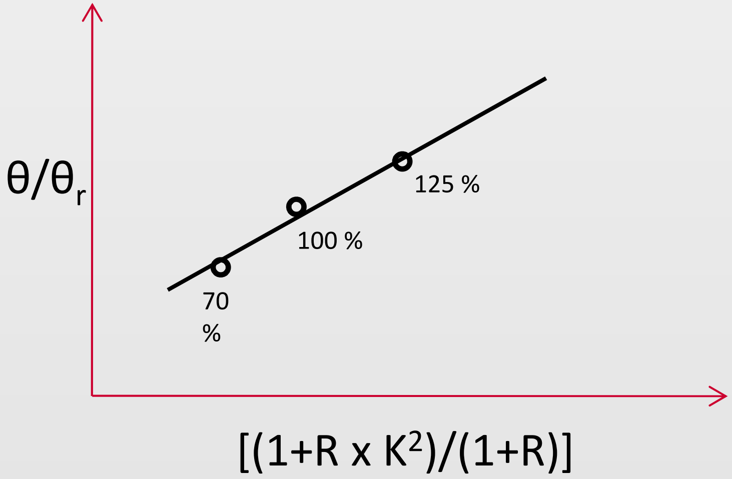
$$\alpha=P/\Delta\theta\Longrightarrow P=C^{te}\bullet\Delta\theta^{1+n}$$

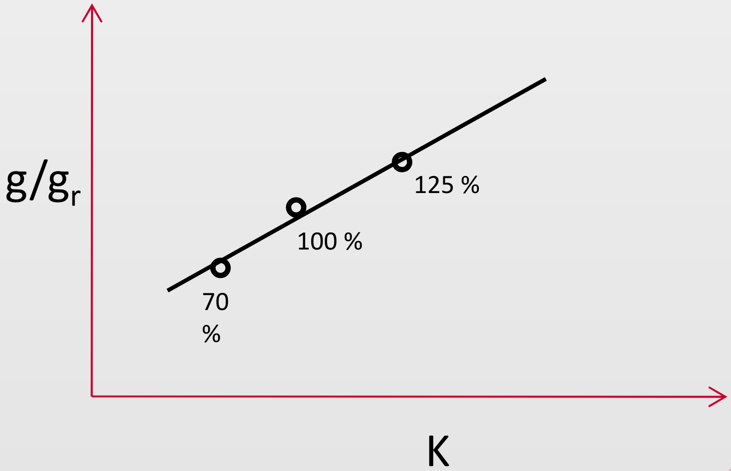
$$\Delta\theta=k\bullet P^{1/(1+n)}=k\bullet P^x$$

Steady State Equations Background

- x exponent (IEEE)
  - exponent x is the slope of the line on log-log chart that bests fits the plot of the top-oil temperature rise measured at the end of three temperature test, (70%, 100% and 125%), versus the loss equation

- y exponent (IEEE)
  - exponent y is the slope of the line on log-log chart that bests fits the plot of the average winding temperature rise above average top-oil temperature measured at the end of three temperature test, (70%, 100% and 125%), versus the loading factor
  - This method assumes that the hot-spot rise over top oil temperature is proportional to the average winding rise over average oil temperature





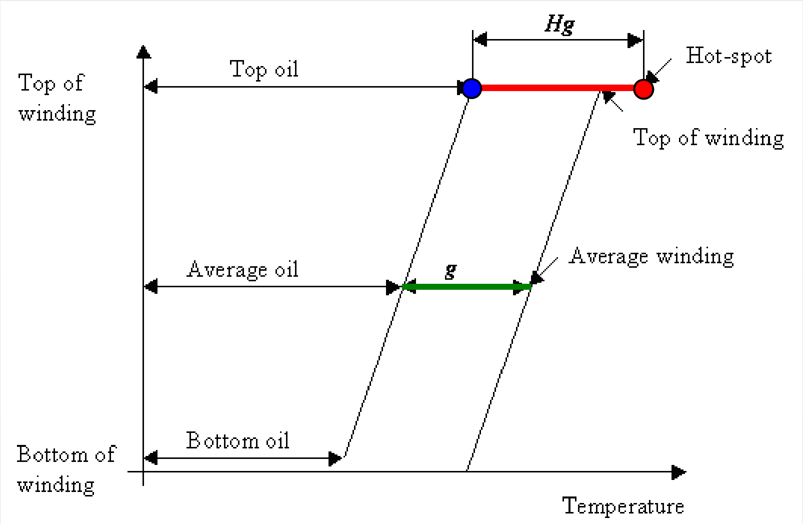
slopes could be determined by the slopes of the lines that best fit the data points plotted using the least-squarer method

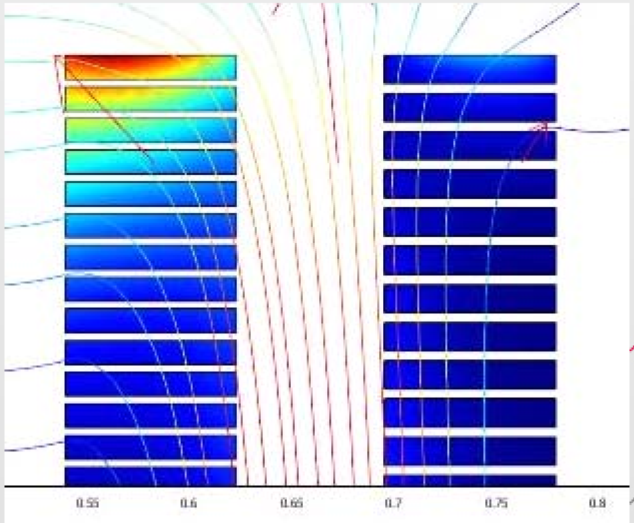
Hot spot factor

- Measurement: Fiber Optic
  - H=(Hot-spot to top oil)/(Average winding to average oil)

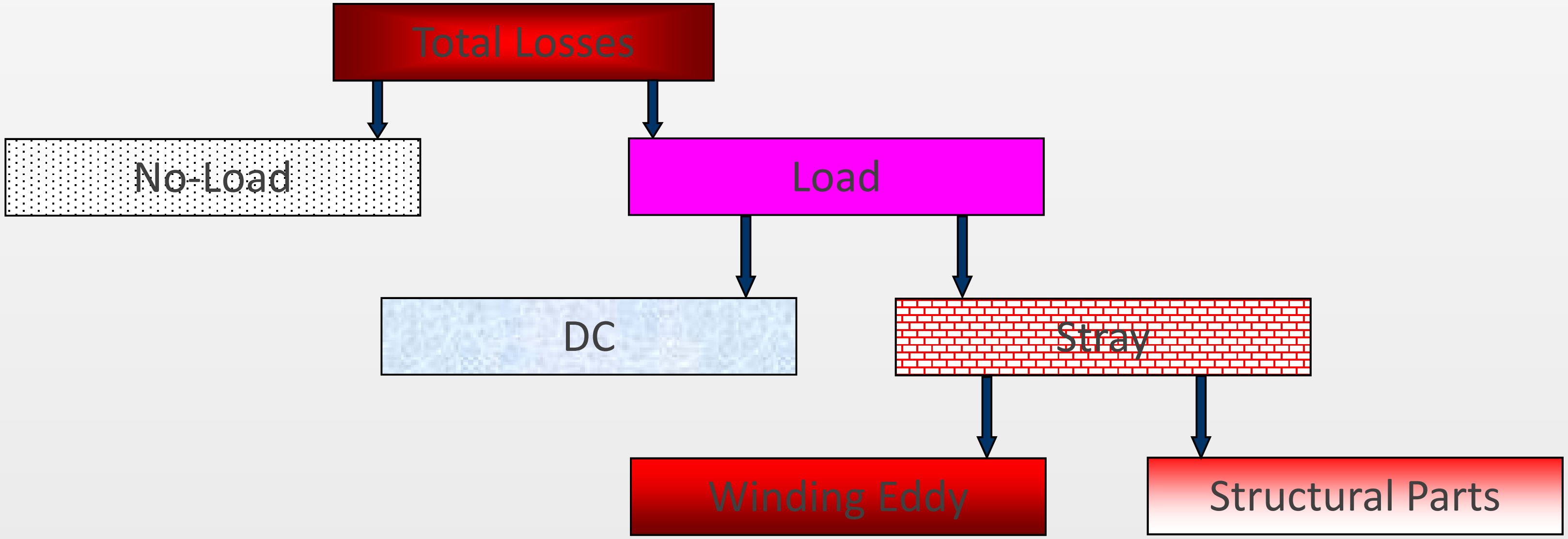
- Calculated:

$$H = \frac{\Delta\theta_{hs-oil}}{g} = \frac{C^{te} \cdot P_{hs}^{y/2}}{C^{te} \times P_{ave}^{y/2}} = \left(\frac{P_{hs}}{P_{ave}}\right)^{y/2}$$





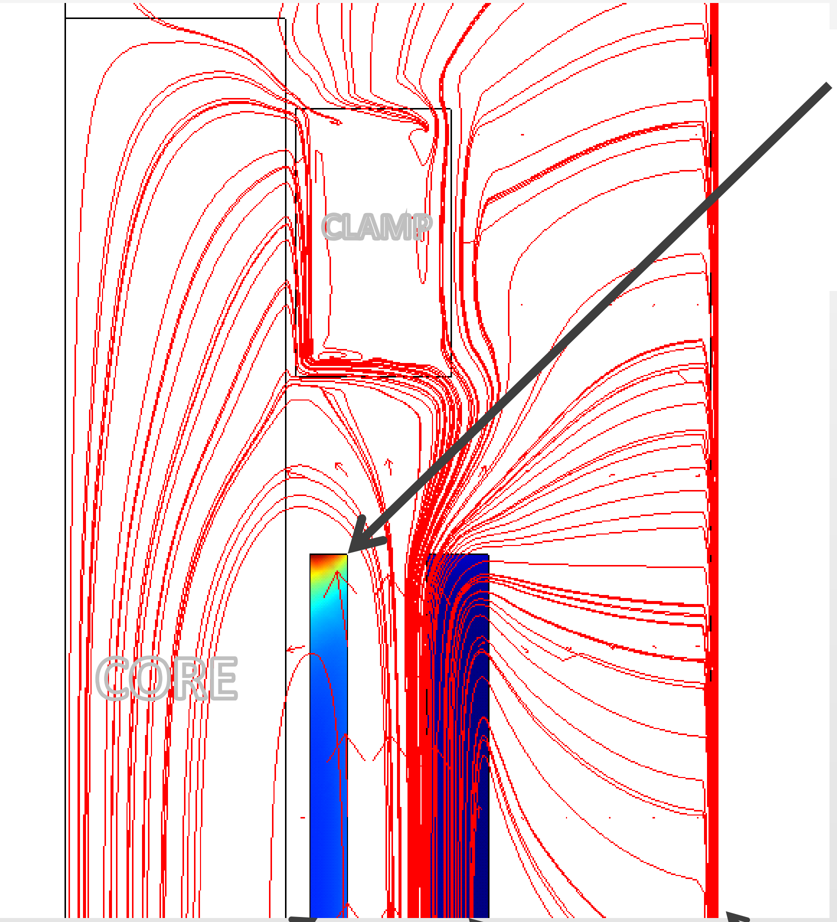
Transformer Losses Classification



- Transformer Total Losses=No-Load Losses + Load Losses
  - Load Losses= DC Losses + Stray Losses
    - Stray Losses=Winding Eddy Losses + Stray Losses in Structural Parts

- Stray Losses=Load Losses-DC Losses (obtained from measurements)

Transformer FEM Model

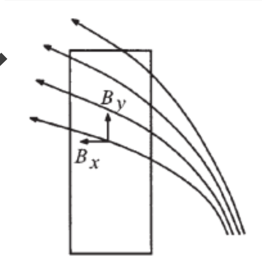


LV Winding

HV Winding

Tank Wall

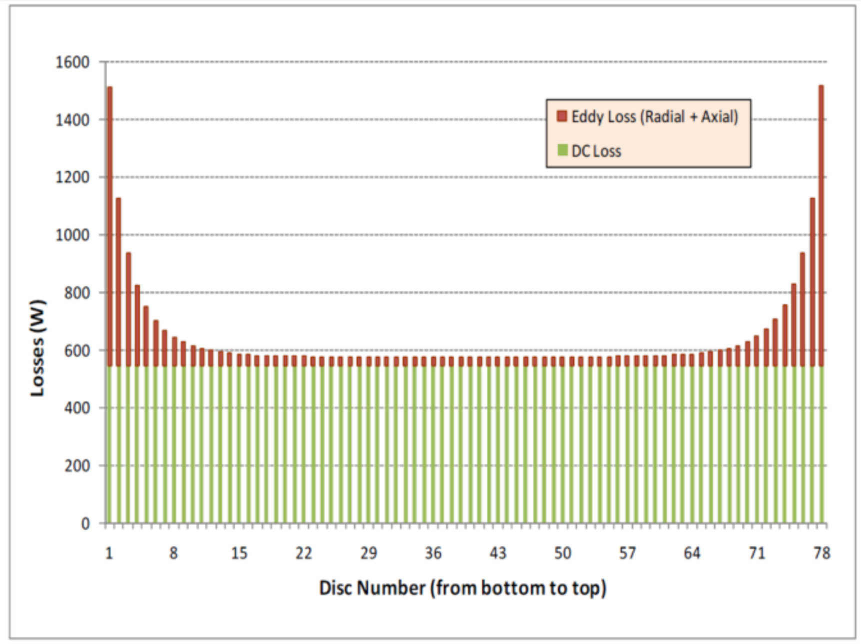
Top Disc Conductor



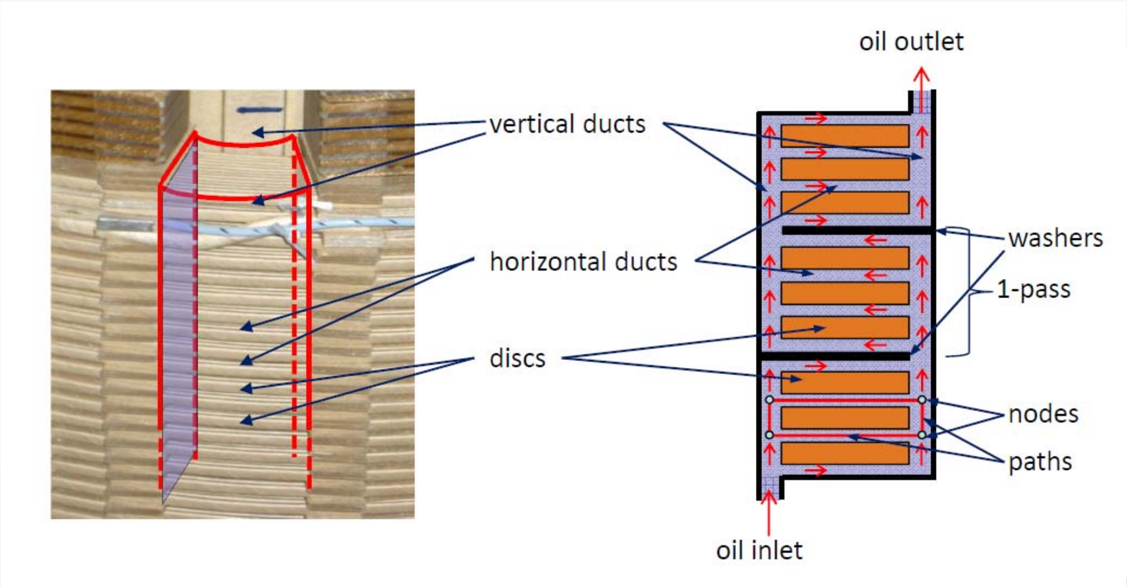
AC/DC Module

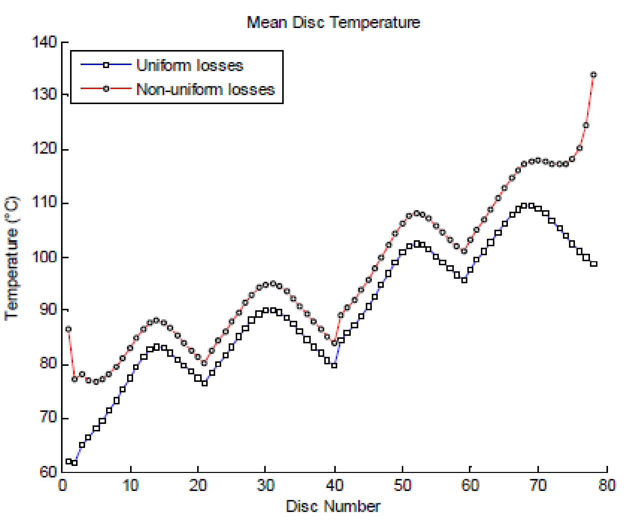
- Maxvell Equations
- Constitutive Relations
- Diffusion Equation

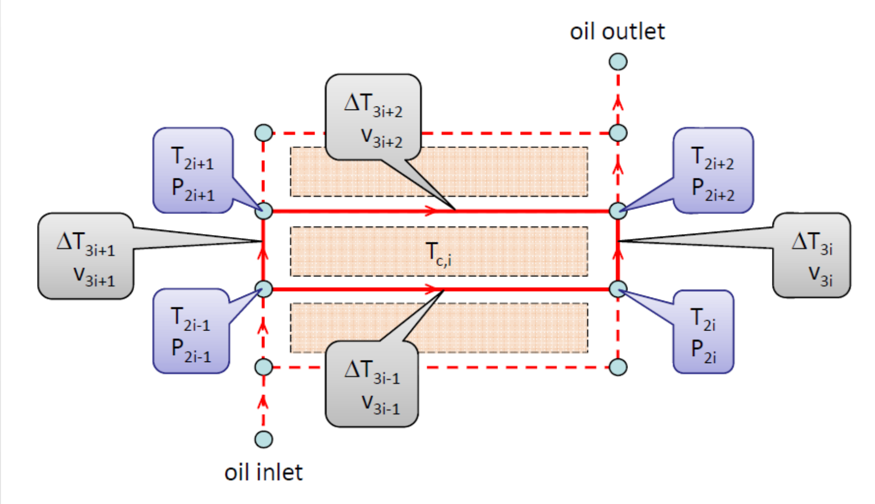
$$P_{EC} = \frac{\pi^2 f^2 T^2 B^2}{3\rho}$$



Thermal Hydraulic Network Model

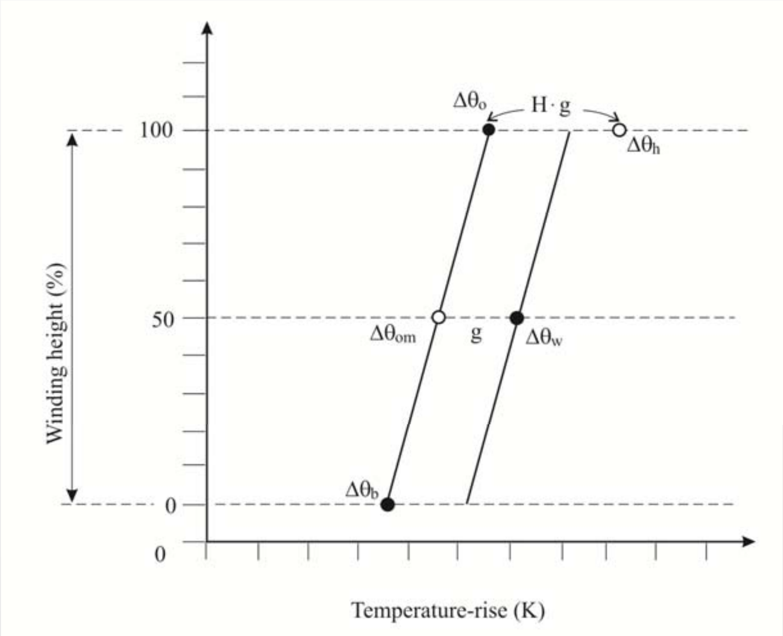






- **Pressure loss equilibrium in closed loops**
- **Conservation of mass at the nodes**
- **Conservation of thermal energy at the nodes**
- **Heat-transfer for each path**

HOT SPOT FACTOR: IEC 60076-2



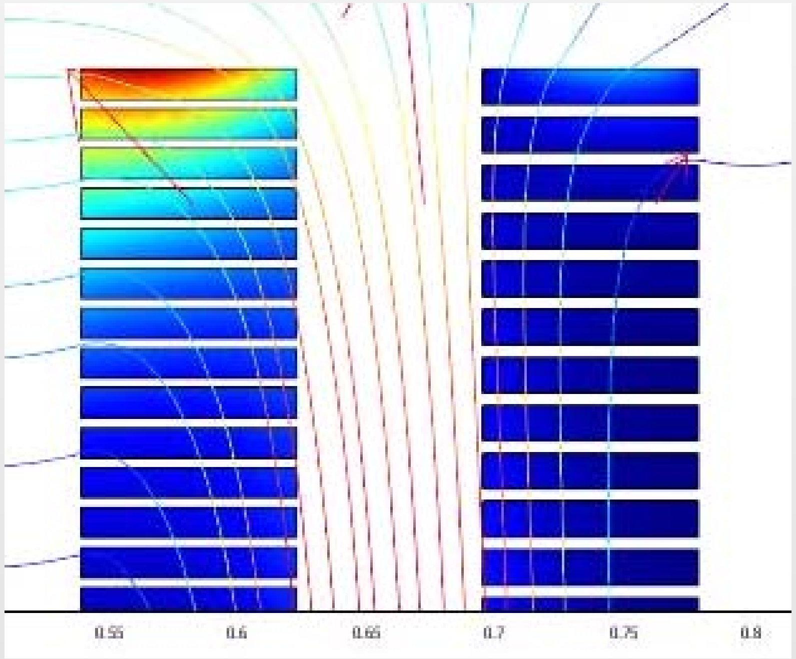
❑ Hot-Spot Factor (H) depends on:

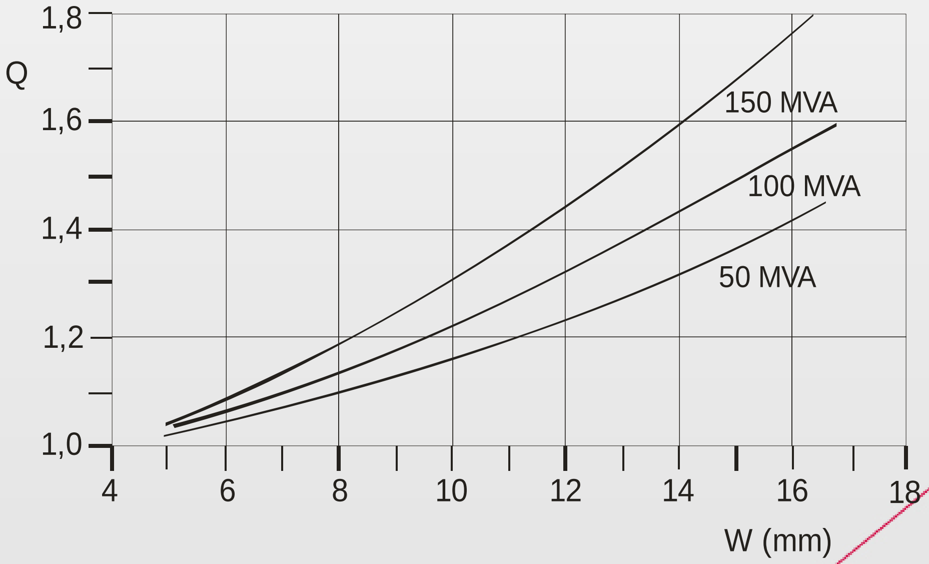
- Q-factor relates to the additional loss and depends on the ratio between the specific loss in the region of the leakage flux concentration (top winding) and the average specific loss of the winding
- S-factor related to the efficiency of liquid cooling circuits inside the winding

H=QxS

Q-factor

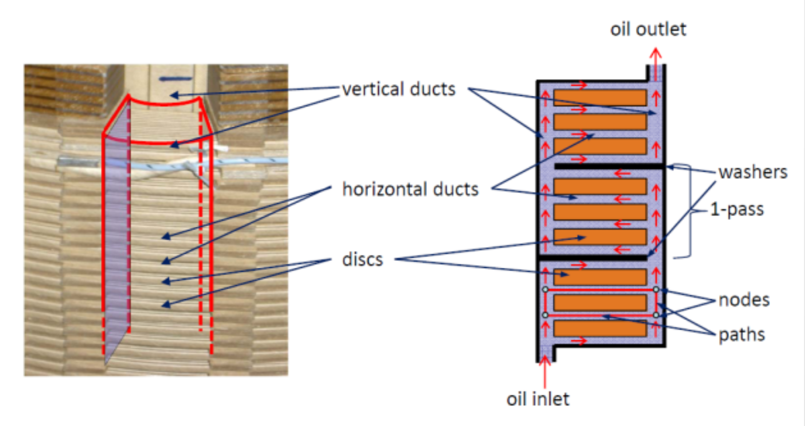
$$Q = \left(\frac{P_{hs}}{P_{ave}} \right)$$

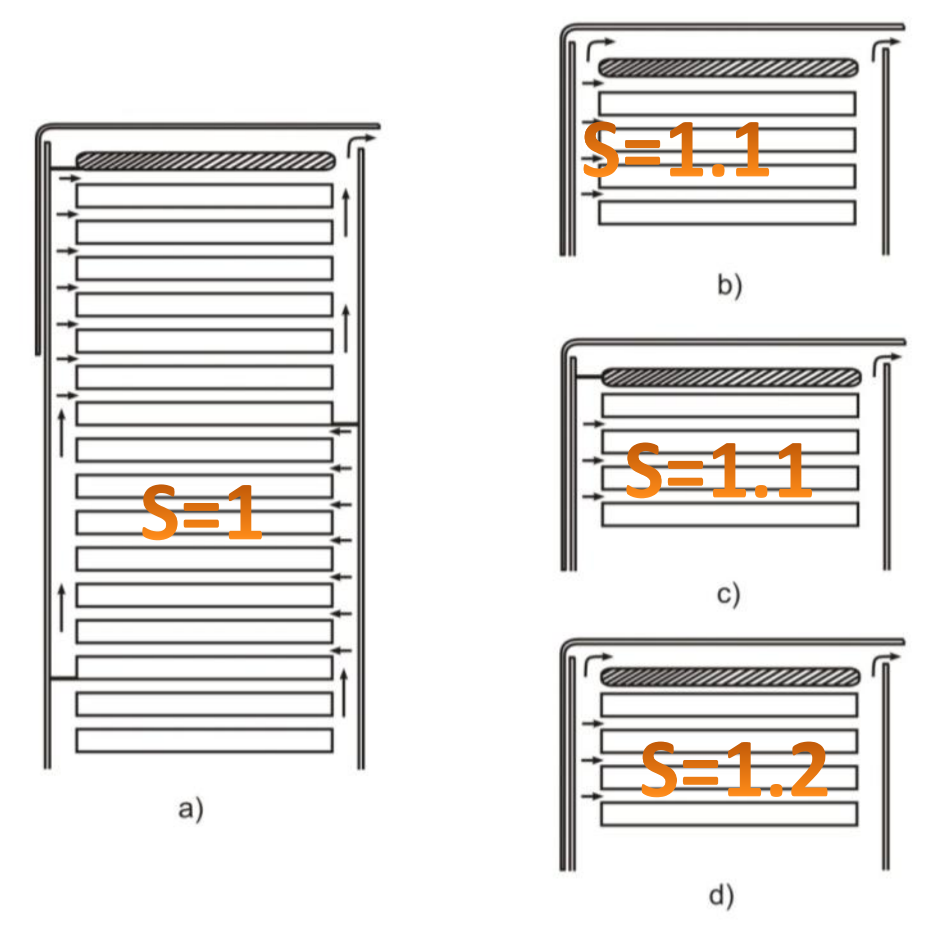




S-factor

- ☐ Evaluation of factor is related to the effects of the cooling liquid circuit, should be made by solving the hydraulic circuit at the top of any specific winding.

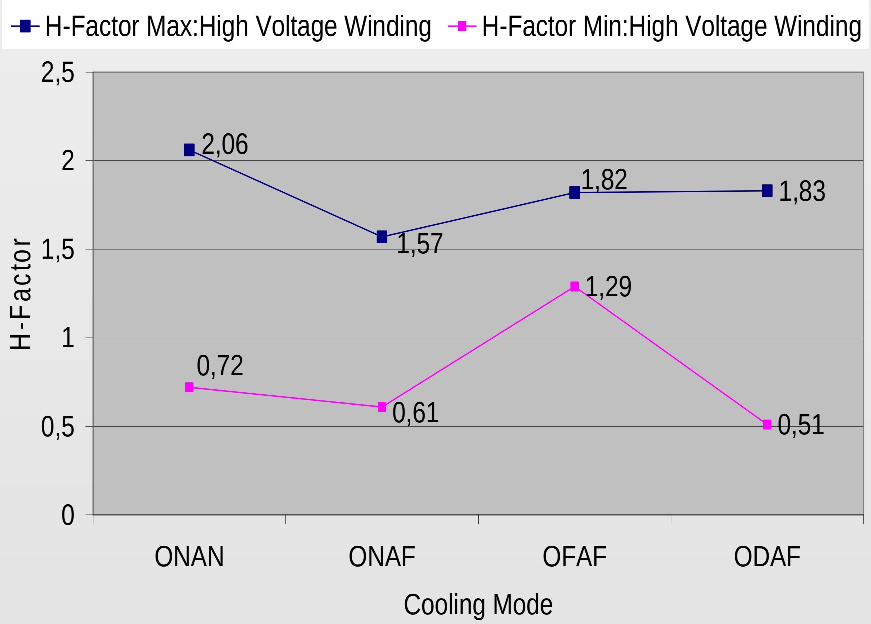


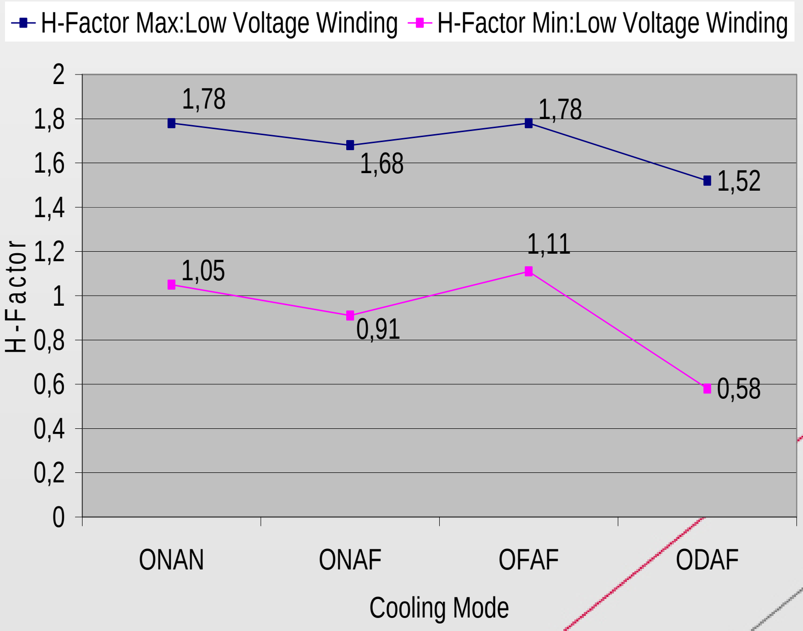


Hot-spot Factor

- ☐ IEC 60076-7
  - ➢ -Distribution Transformers: H=1.1
  - ➢ -Medium and Large Power Transformer ONAN, ONAF, OFAF, ODAF: H=1.3

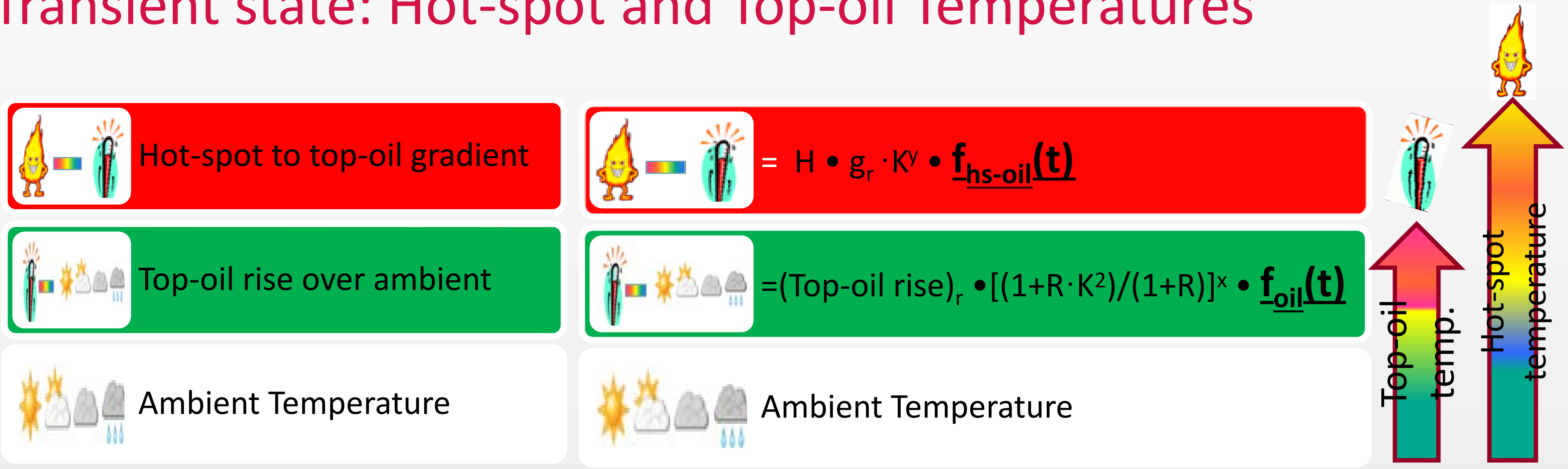
- ☐ CIGRE WG12.09 Report: Experimental Determination of Power Transformer Hot-Spot Factor





Statnett

Transient state: Hot-spot and Top-oil Temperatures



Hot-spot to top-oil gradient

$= H \bullet g_r \cdot K^y \bullet \underline{f_{hs\text{-}oil}(t)}$

Top-oil rise over ambient

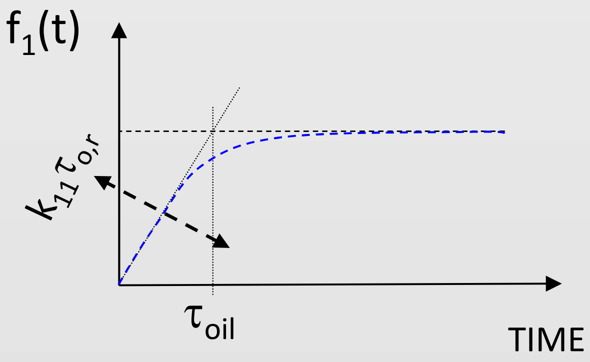
$=(\text{Top-oil rise})_r \bullet [(1+R\cdot K^2)/(1+R)]^x \bullet \underline{f_{oil}(t)}$

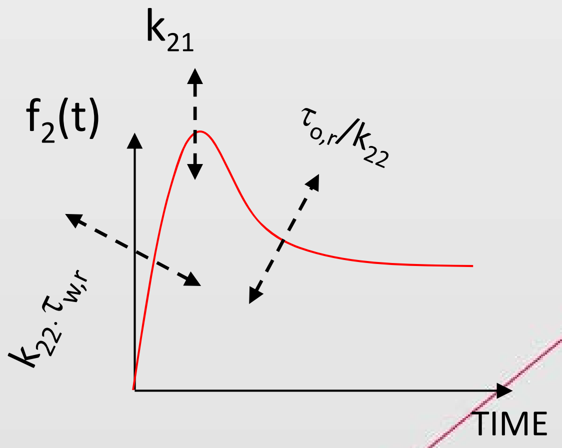
Ambient Temperature

Ambient Temperature

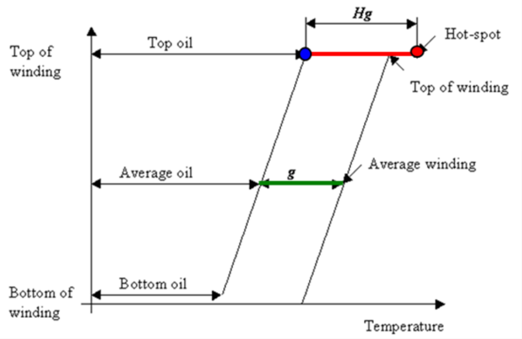
$$\mathbf{f_{oil}(t)}=f_1(t)=(1-e^{-t/(k_{11}\cdot\tau_{o,r})})$$

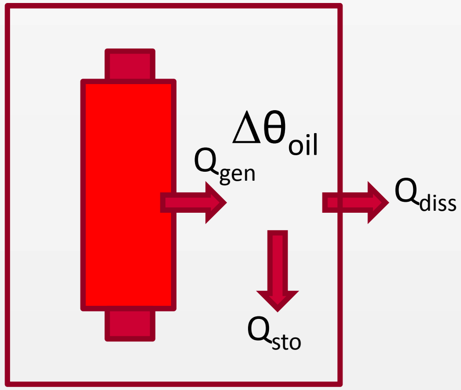
$$\mathbf{f_{hs\text{-}oil}(t)}=f_2(t)=k_{21}[1-e^{-t/(k_{22}\tau_{w,r})}]-(k_{21}-1)\ [1-e^{-t/(\tau_o/k_{22})}]$$





Transient State: Top-oil model background



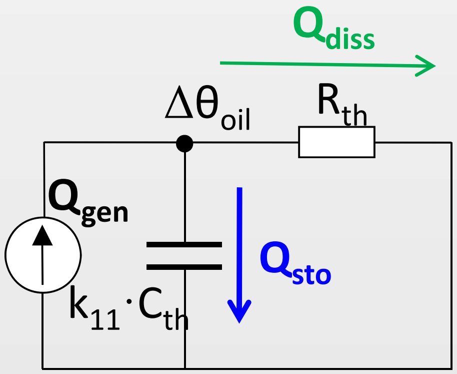


Heat balance equation:

$$Q_{gen} = Q_{sto} + Q_{diss}$$

$$(P_l + P_{fe}) \cdot \delta t = k_{11} \cdot C_{th} \cdot \delta\Delta\theta_{oil} + \Delta\theta_{oil} / R_{th}$$

$$(P_l + P_{fe}) \cdot R_{th} = k_{11} \cdot C_{th} \cdot R_{th} \cdot (\delta\Delta\theta_{oil}/\delta t) + \Delta\theta_{oil}$$



Considering:

❑steady state temperature rises

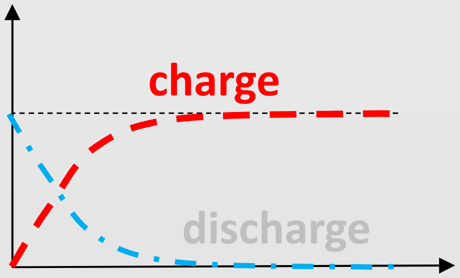
❑$C_{th} \cdot R_{th} = (C_{th} \cdot R_{th})_{rated} = \tau_{oil,rated}$

❑$(P_l + P_{fe})_r \cdot R_{th,r} = \Delta\theta_{oil,r}$

❑$(P_l + P_{fe}) \cdot R_{th} = \Delta\theta_{oil,final} = \Delta\theta_r \bullet [(1+R \bullet K^2)/(1+R)]^x$

Final differential equation for observed process :

$$\Delta\theta_r \bullet [(1+R \bullet K^2)/(1+R)]^x = k_{11} \cdot \tau_{oil,rated} \cdot (\delta\Delta\theta_{oil} / \delta t) + \Delta\theta_{oil}$$

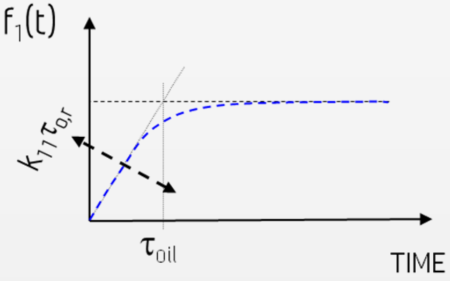


$$\Delta\theta_{oil}(t) = \Delta\theta_{oi} + \left\{ \Delta\theta_{oil,r} \cdot \left[\frac{1+R \cdot K^2}{1+R} \right]^x - \Delta\theta_{oi} \right\} \times \left(1 - e^{(-t)/(k_{11} \cdot \tau_{0,r})} \right)$$

$$\Delta\theta_{oil}(t) = \Delta\theta_{oil,r} \cdot \left[\frac{1+R \cdot K^2}{1+R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{oil,r} \times \left[\frac{1+R \cdot K^2}{1+R} \right]^x \right\} \cdot e^{(-t)/(k_{11} \cdot \tau_{0,r})}$$

Statnett

Transient State: Top-Oil Time Constant



- Calculated:

$$\tau_{o,r} = \frac{C_{th-oil} \times \Delta\theta_{om,rated}}{P_{tot}}$$

$$C_{th-oil} = 0{,}132 \times m_A + 0{,}0882 \times m_T + 0{,}4 \times m_o$$

- 0.132 –the ratio of iron to copper in a transformer is about 5 or 6 to 1, therefore the metal can be lumped together and multiplied by the specific heat coefficient for iron
- 0.0882=2/3x0.132-the base of the tank, the bottom end of the wall and the cover dissipate very little heat, therefore 2/3 of the tank weight is taken
- 0.4=0.51x0,8-all the oil in transformer is not heated to the same temperature as the top oil. There is top to bottom oil gradient. The ratio of average to maximum oil temperature gradients ranges from about 70% to 95%, depending on design. An average of these ratios is approximately 80%

Transient State: constant k_{11}

constant k_{11} should be estimated for the transient top-oil rise temperature curve obtained during the test period with total losses

obtained measured relative increase of the top-oil temperature rise as per unit of the steady state value, Mf_{1j}, for the complete test period

$$Mf_{1j} = \frac{M\theta_{o_j} - M\theta_{a_j}}{\Delta\theta_{or}}$$

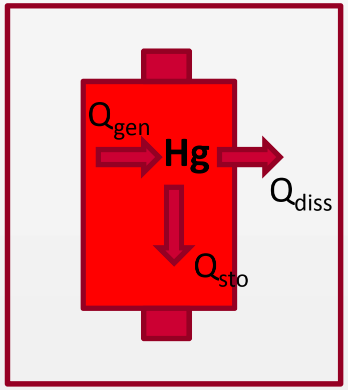
perform nonlinear regression by using guess-error approach, (alternatively excel solver could be used), to find the constant to minimize the sum of squares of differences between f_{1j} and Mf_{1j}

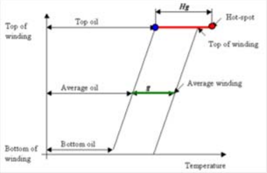
$$minimize : \sum_{j=1}^{N} \left[f_1(x)_j - Mf_{1j} \right]^2$$

M indicates measured variable
x is a vector whose element is only k_{11} thermal time constant
f_{1j} is the relative increase of the top-oil temperature rise as per unit of the steady state value
Mf_{1j} is the measured relative increase of the top-oil temperature rise as per unit of the steady state value
j is the index for each time step over the test period with total losses

Statnett

Transient state: Hot-Spot to Top-Oil Gradient Model



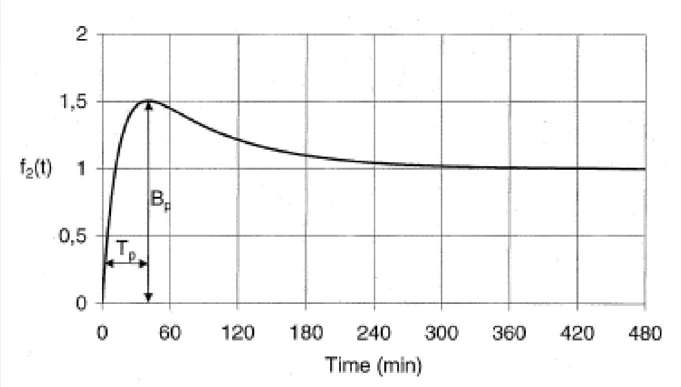


Modelling Limitation:

1. **Hg** gradient does not vary with time according to the exponential curve similar to top-oil rise. It follows an overshot function.
2. Temperature gradient starts increasing instantly with heat generation
3. Dissipation has a certain time lag as it takes some time before the oil circulation has adapted its speed to correspond to the increased load level. During this time lag generated heat is only stored
4. Heat balance equation cannot be directly applied to **Hg** gradient in the form used for the top-oil model
5. **"Superimposed" Modelling with and without oil cooling effect**

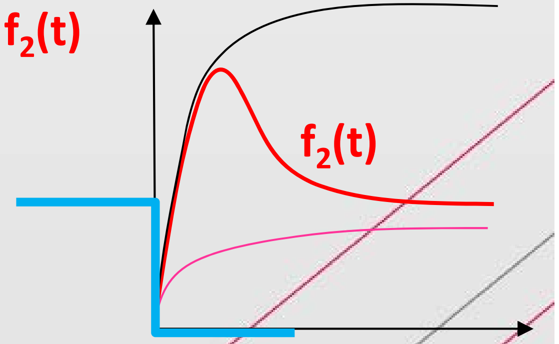
Solution at load increase:

$$\boxed{\Delta\theta_{h-o}(t) = \Delta\theta_{h\text{-}o_i} + \left\{Hg_r K^y - \Delta\theta_{h\text{-}o_i}\right\} \cdot \left\{k_{21} \cdot \left(1 - e^{(-t)/(k_{22}\cdot\tau_{\mathrm{w,r}})}\right) - \left(k_{21} - 1\right) \cdot \left(1 - e^{(-t)/(\tau_{0,r}/k_{22})}\right)\right\}}$$

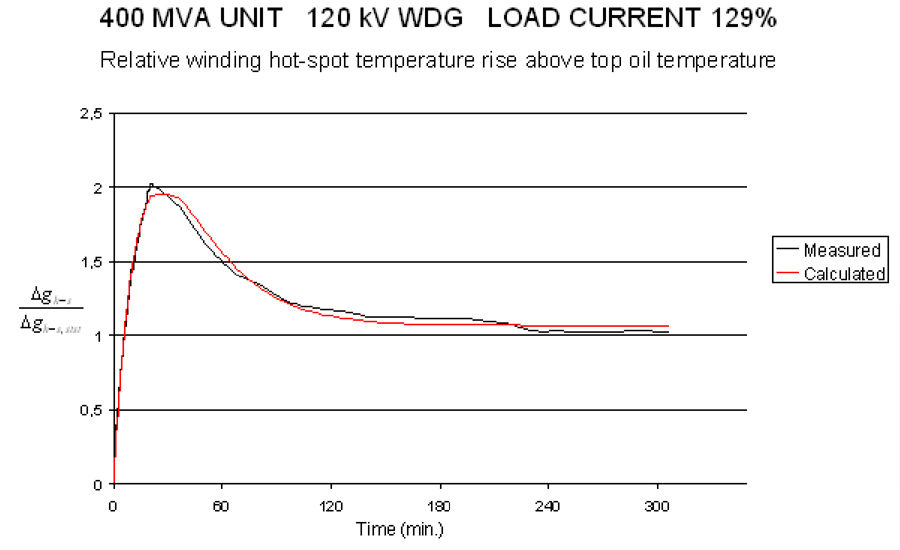


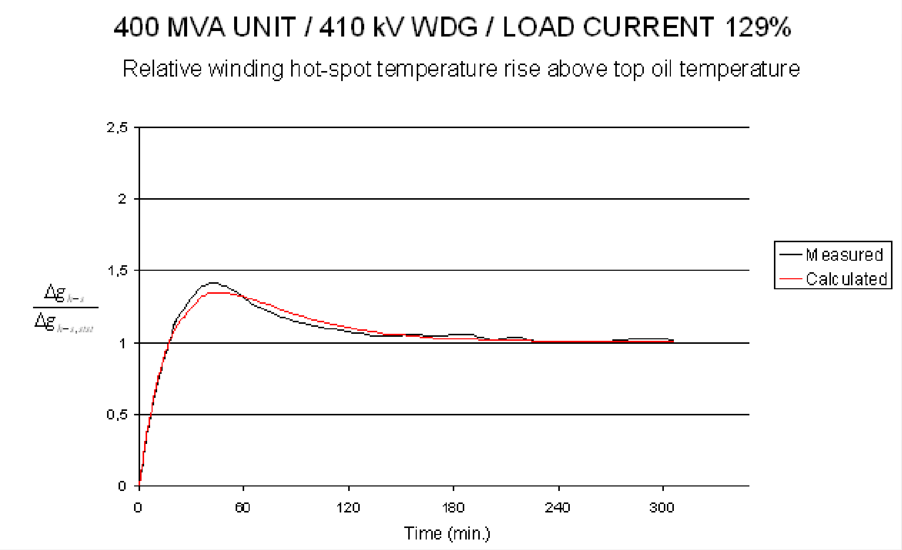
Solution at load decrease:

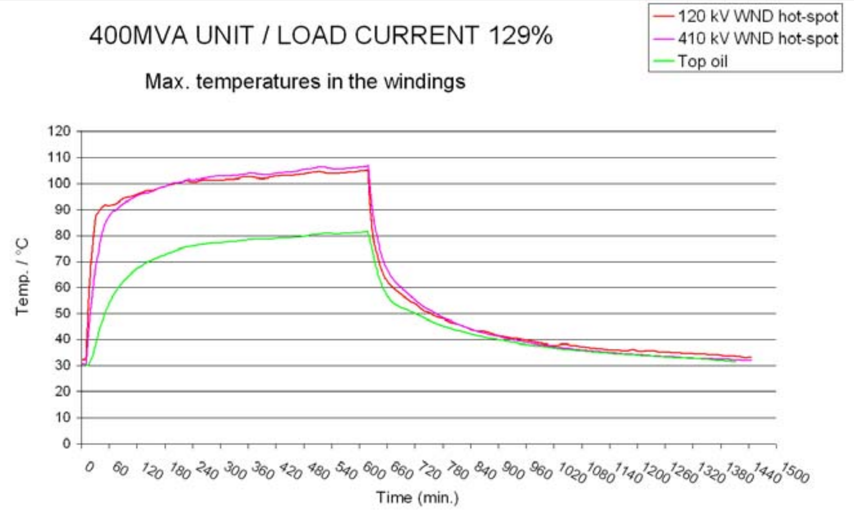
$$\boxed{\Delta\theta_{h-o}(t) = Hg_r K^y}$$



Transient state: Hot-Spot to Top-Oil Gradient Model







Statnett

Transient state: Winding Time Constant

$$\tau_{w,r} = \frac{m_w \times c \times g_r}{60 \times P_{w,r}}$$

$$\tau_{w,r} = 2.75 \times \frac{g_r}{(1 + P_{e,r}) \times s_r^2} \qquad Cu$$

$$\tau_{w,r} = 1.15 \times \frac{g_r}{(1 + P_{e,r}) \times s_r^2} \qquad Al$$

$\tau_{w,r}$ is the winding time constant

g_r is the average winding to average oil gradient

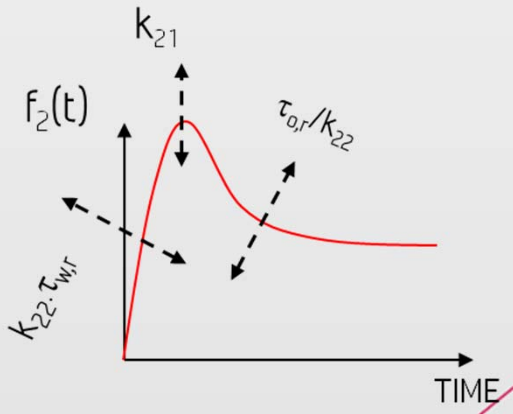
m_w is the mass of the winding in kg

c is the specific heat of the winding

$P_{w,r}$ is the winding loss

$P_{e,r}$ is the relative winding eddy loss

s_r is the current density



k_{21} and k_{22} constants

obtained measured relative increase of the hot-spot to top-oil gradient, Mf_{2j}, as per unit of the steady state value for the complete test period

$$Mf_{2_j} = \frac{M\theta_{h_j} - M\theta_{o_j}}{\Delta\theta_{h-o,steady\_state}}$$

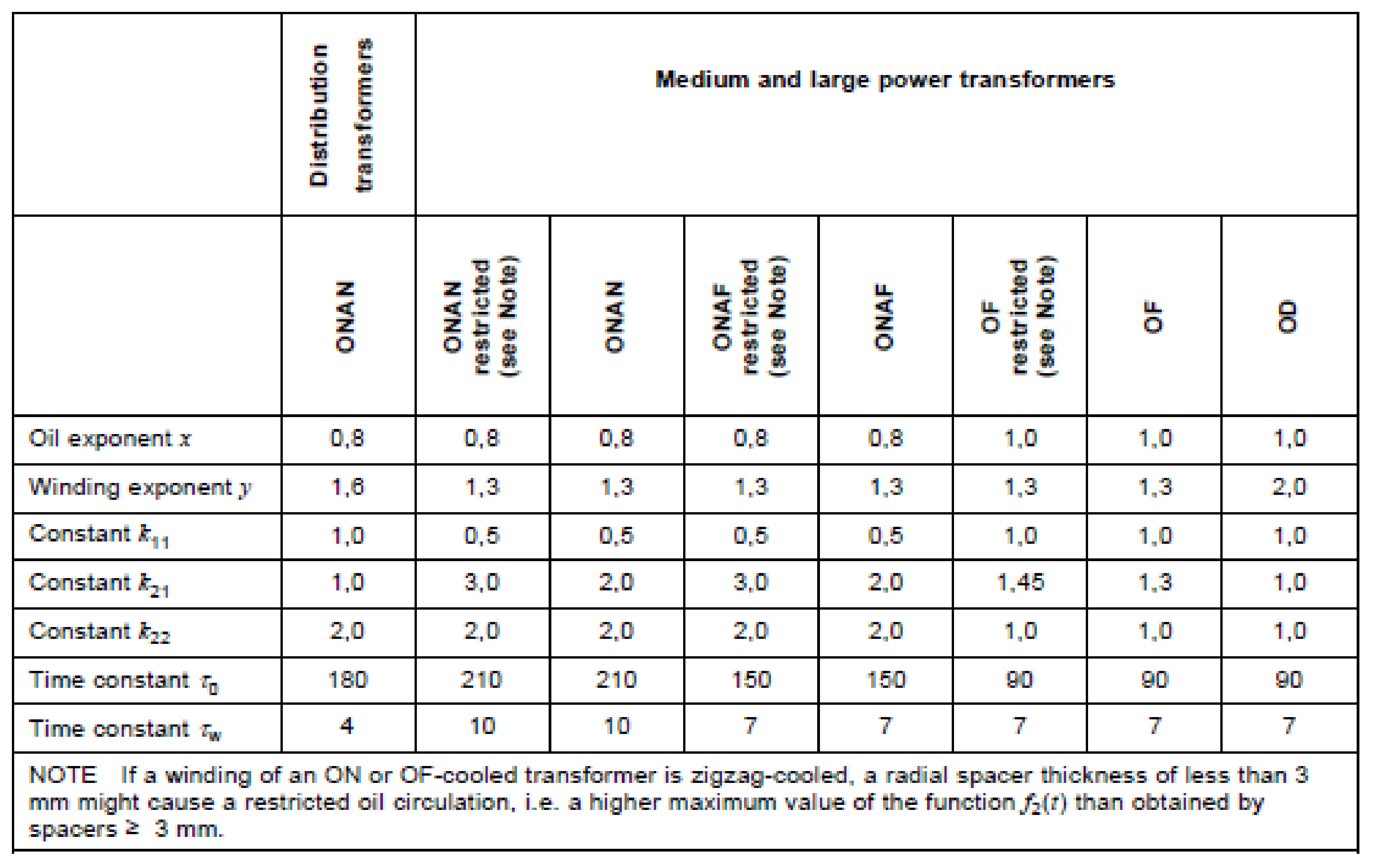
perform nonlinear regression by using guess-error approach, (alternatively excel solver could be used), to find the constant to minimize the sum of squares of differences between f_{2j} and Mf_{2j}

$$min\,imize = \sum_{j=1}^{N} \left[f_2(x)_j - Mf_{2_j} \right]^2$$

introduce the following constraint: maximum of f_{2j} is equal to maximum of Mf_{2j}

M indicates measured variable
x is a vector whose elements are k_{21} and k_{22} constants
f_{2j} is the relative increase of the hot-spot to top-oil gradient as per unit of the steady state value
Mf_{2j} is the measured relative increase of the hot-spot to top-oil gradient as per unit of the steady state value
j is the index for each step over the test period with total losses

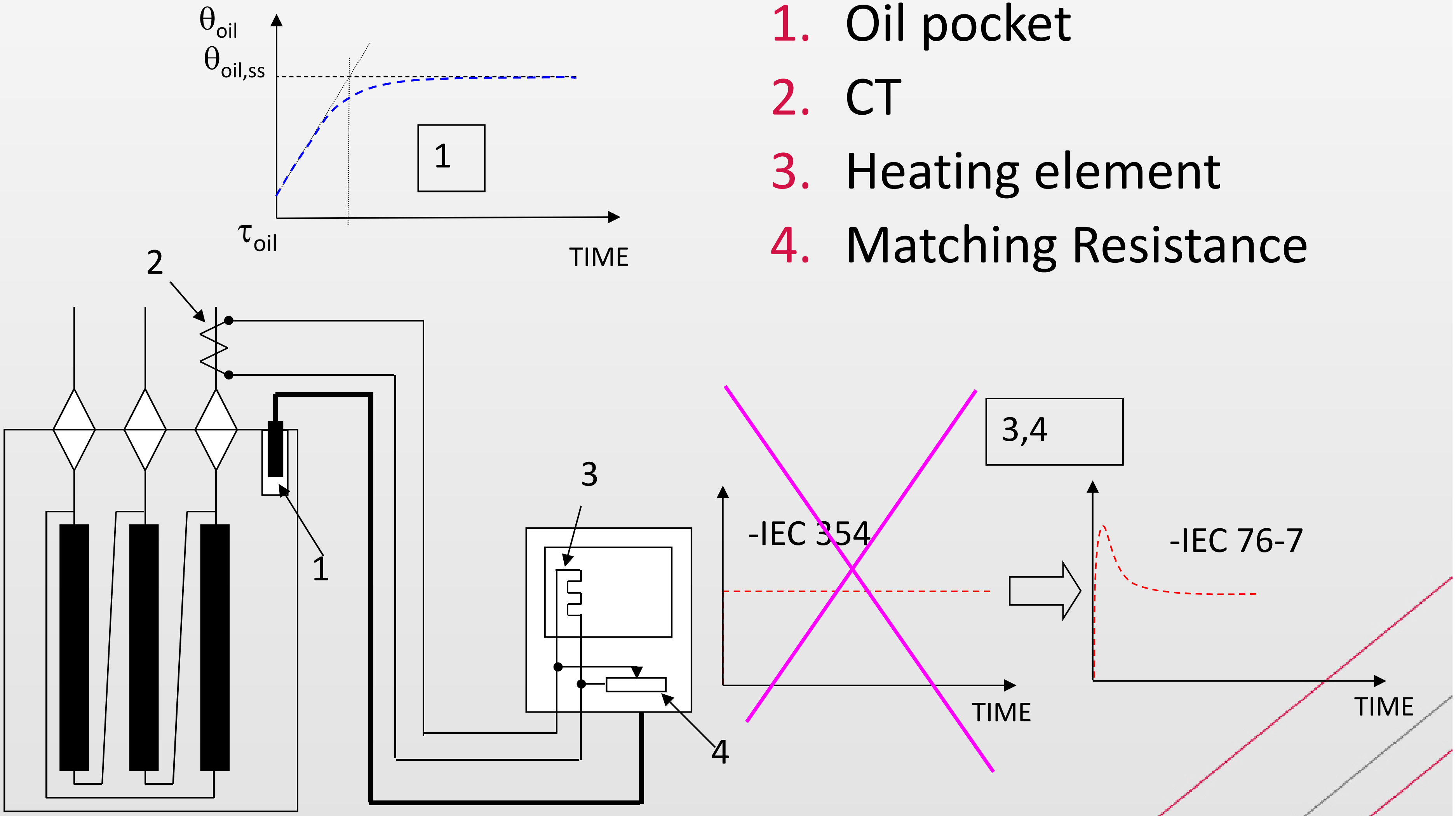
Recommended thermal characteristics for exponential equations



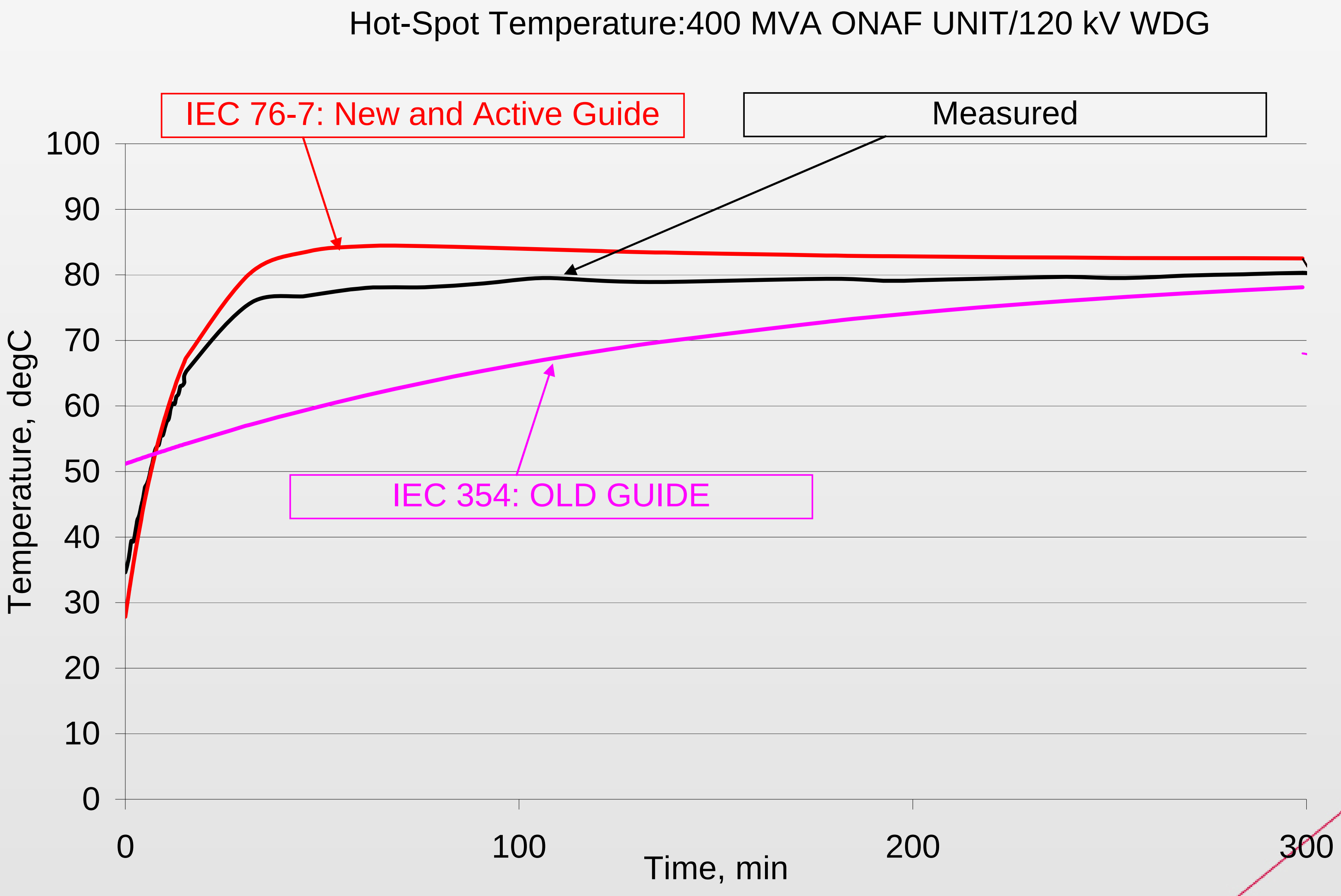
	Distribution transformers	Medium and large power transformers						
	ONAN	ONAN restricted (see Note)	ONAN	ONAF restricted (see Note)	ONAF	OF restricted (see Note)	OF	OD
Oil exponent x	0,8	0,8	0,8	0,8	0,8	1,0	1,0	1,0
Winding exponent y	1,6	1,3	1,3	1,3	1,3	1,3	1,3	2,0
Constant k_{11}	1,0	0,5	0,5	0,5	0,5	1,0	1,0	1,0
Constant k_{21}	1,0	3,0	2,0	3,0	2,0	1,45	1,3	1,0
Constant k_{22}	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0
Time constant τ_0	180	210	210	150	150	90	90	90
Time constant τ_w	4	10	10	7	7	7	7	7

NOTE If a winding of an ON or OF-cooled transformer is zigzag-cooled, a radial spacer thickness of less than 3 mm might cause a restricted oil circulation, i.e. a higher maximum value of the function $f_2(t)$ than obtained by spacers ≥ 3 mm.

IEC 60076-7 versus IEC 354

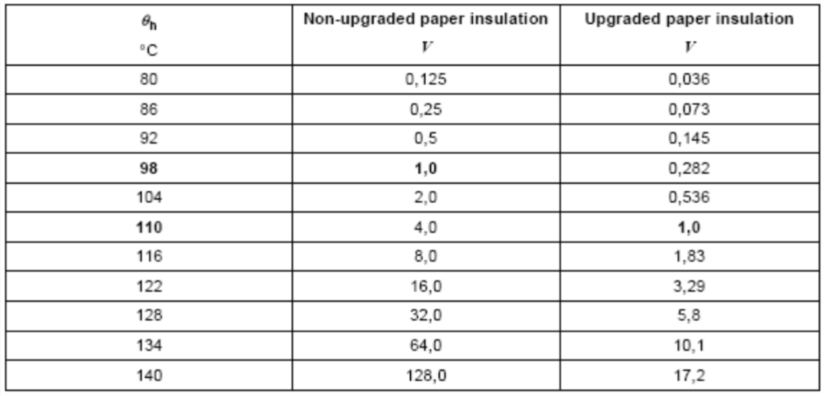


1. Oil pocket
2. CT
3. Heating element
4. Matching Resistance


Hot-Spot Temperature:400 MVA ONAF UNIT/120 kV WDG
IEC 76-7: New and Active Guide
Measured
IEC 354: OLD GUIDE
Temperature, degC
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
Time, min

Example: Loss of Life (IEC 60076-7)

- ☐ Relative Aging Rate due to Hot-Spot Temperature (*V*):
  - Non-thermally Upgraded Paper $$V = 2^{(\theta_h - 98)/6}$$
  - Thermally Upgraded Paper $$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h + 273}\right)}$$
  - The relative ageing rate *V* = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and to 110 °C for thermally upgraded paper:



θ_h °C	Non-upgraded paper insulation V	Upgraded paper insulation V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	**1,0**	0,282
104	2,0	0,536
110	4,0	**1,0**
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2

- ☐ Loss-of-Life (L)
  - *Over certain period:* $L = \Sigma V_n x t_n$, *where n(1,N)*

Loss of Life (SINTEF)

- ❑ Relative Aging Rate due to Hot-Spot Temperature (*V*):

  - ➢ Non-thermally Upgraded Paper & Thermally Upgraded Paper

$$V = \frac{A}{A_B} e^{\left(\frac{E_B}{R(\theta_B + 273)} - \frac{E}{R(\theta_h + 273)}\right)}$$

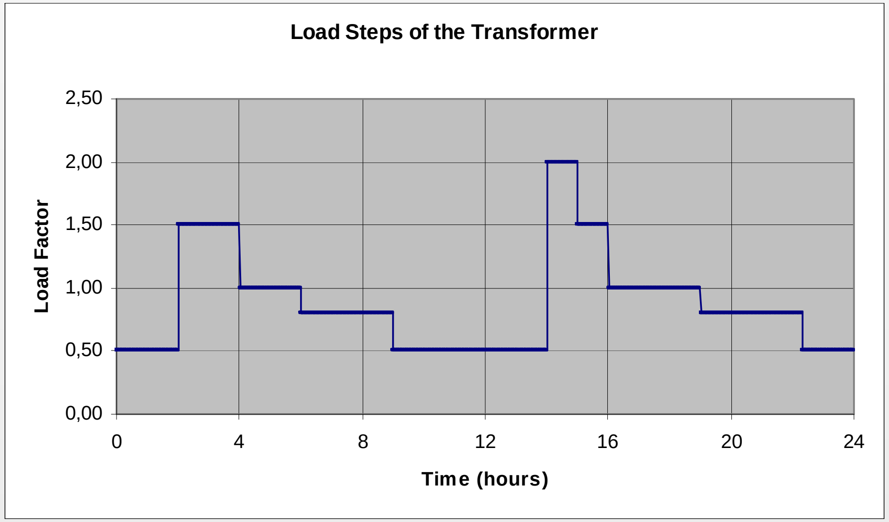
■Where: A-environmental factor, E-activation energy, B-basic dry&clean condition, R-molar gas constant

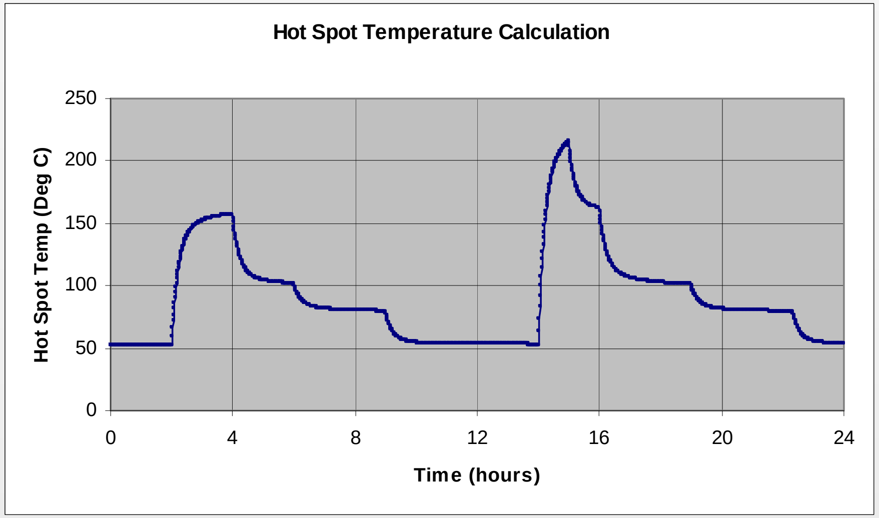
■The relative ageing rate *V* = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and to 110 °C for thermally upgraded paper:

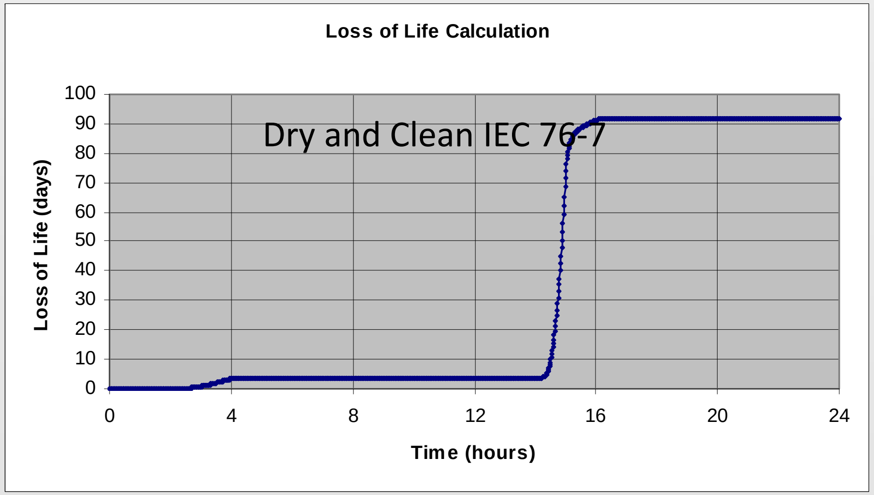
Non-Upgarded Insulation					
Temperature	IEC 76-7	Dry&Clean	1.5% moisture	3,5 % moisture	Dry&Oxygen
80	0,125	0,121	0,441	1,323	0,798
86	0,25	0,250	0,914	2,742	1,325
92	0,5	0,506	1,849	5,548	2,163
98	***1***	***1,000***	***3,659***	***10,976***	***3,477***
104	2	1,936	7,082	21,245	5,503
110	4	3,670	13,427	40,281	8,586
116	8	6,822	24,960	74,880	13,213
122	16	12,446	45,534	136,601	20,069
128	32	22,300	81,585	244,755	30,105
134	64	39,274	143,687	431,061	44,622
140	128	68,042	248,934	746,802	65,388

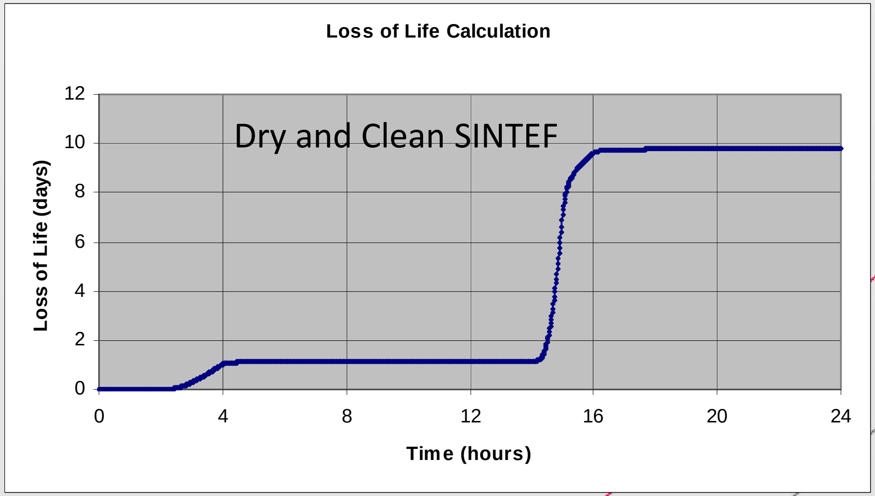
Upgraded Paper Insulation					
Temperature	IEC 76-7	Dry&Clean	1.5% moisture	3,5 % moisture	Dry&Oxygen
80	0,036	0,101	0,189	0,384	0,787
86	0,073	0,164	0,308	0,627	1,256
92	0,145	0,264	0,495	1,006	1,973
98	0,282	0,417	0,783	1,592	3,054
104	0,536	0,651	1,220	2,480	4,662
110	***1,000***	***1,000***	***1,875***	***3,813***	***7,024***
116	1,830	1,517	2,844	5,783	10,449
122	3,286	2,272	4,259	8,661	15,358
128	5,801	3,361	6,302	12,815	22,315
134	10,069	4,917	9,218	18,744	32,068
140	17,199	7,112	13,336	27,116	45,600

Loss of Life Example


Load Steps of the Transformer


Hot Spot Temperature Calculation


Loss of Life Calculation


Loss of Life Calculation